STATUS OF THE COMBINED CYCLE ENGINE RIG

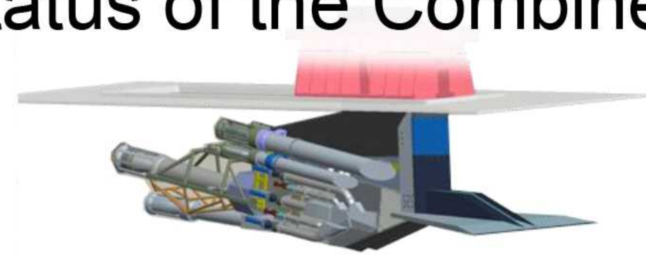
Status for the past year is provided of the turbine-based Combined-Cycle Engine (CCE) Rig for the hypersonic project. As part of the first stage propulsion of a two-stage-to-orbit vehicle concept, this engine rig is designed with a common inlet that supplies flow to a turbine engine and a dual-mode ramjet / scramjet engine in an over/under configuration. At Mach 4 the inlet has variable geometry to switch the airflow from the turbine to the ramjet / scramjet engine. This process is known as inlet mode-transition. In addition to investigating inlet aspects of mode transition, the rig will allow testing of turbine and scramjet systems later in the test series. Fully closing the splitter cowl "cocoons" the turbine engine and increases airflow to the scramjet duct. The CCE Rig will be a testbed to investigate integrated propulsion system and controls technology objectives. Four phases of testing are planned to 1) characterize the dual inlet database, 2) collect inlet dynamics using system identification techniques, 3) implement an inlet control to demonstrate mode-transition scenarios and 4) demonstrate integrated inlet/turbine engine operation through mode-transition. Status of the test planning and preparation activities is summarized with background on the inlet design and small-scale testing, analytical CFD predictions and some details of the large-scale hardware. The final stages of fabrication are underway.

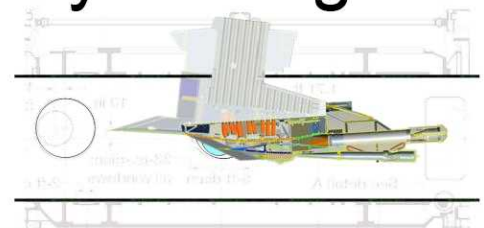
National Aeronautics and Space Administration

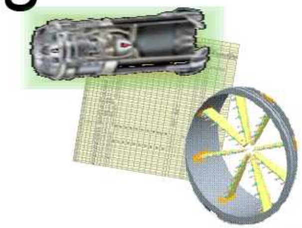
Hypersonics Project

Status of the Combined Cycle Engine Rig

Dave Saunders
John Slater
Vance Dippold



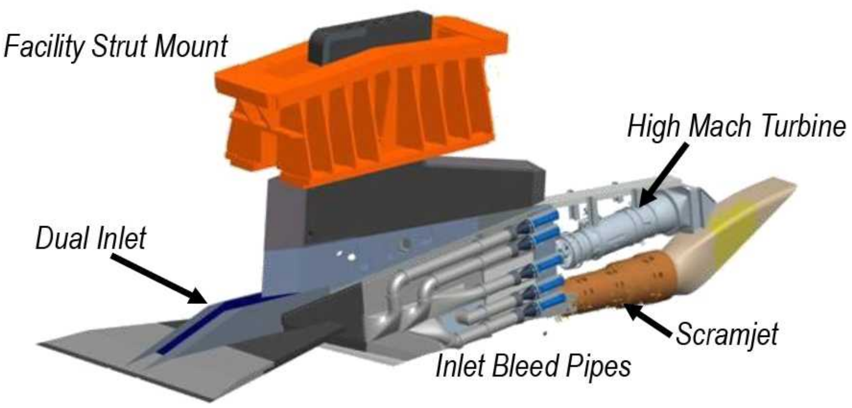




2009 Annual Meeting
September 29-October 1, 2009

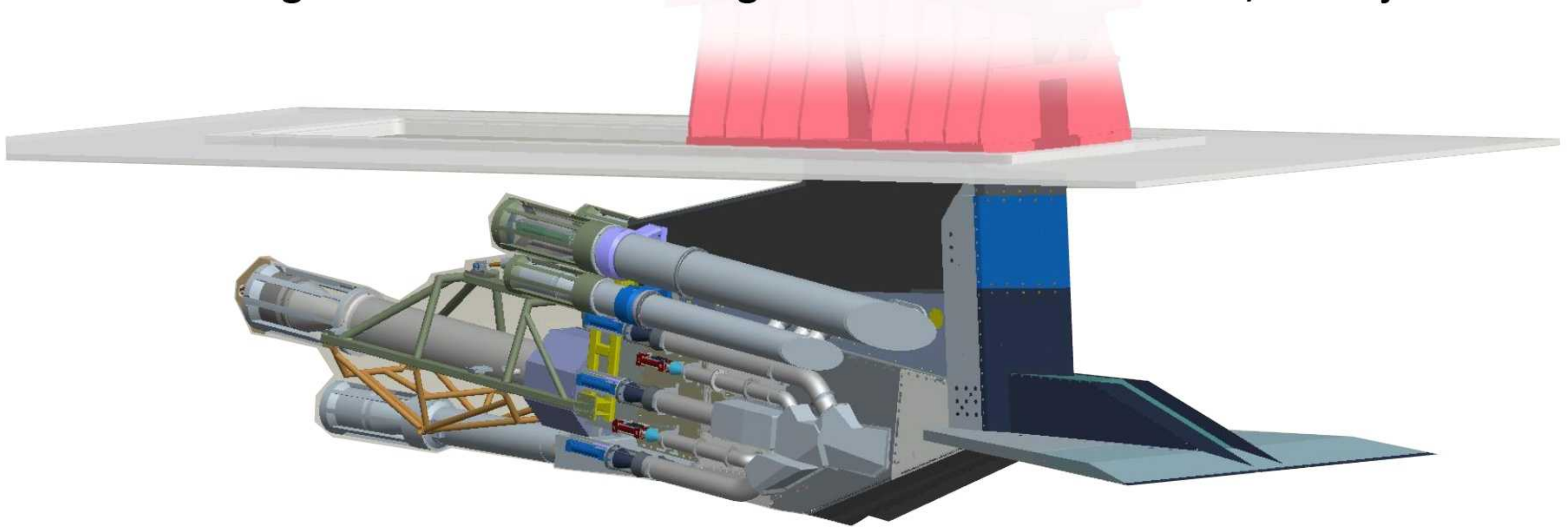
Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, how, when, who, why?
- Background: Inlet Design / small-scale test
- CFD predictions
- Test Planning
- Instrumentation
- Summary



What is CCE mode transition?

Combined Cycle Engine mode transition is a research and demonstration project to show high propulsion performance can be maintained while transitioning between a turbine engine and a dual mode ram/scramjet

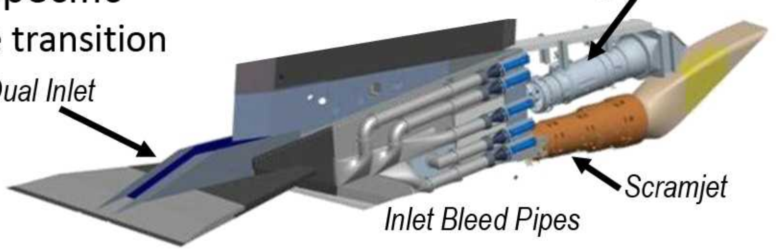


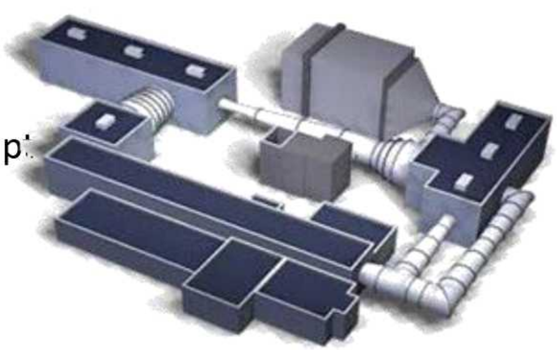
- Inlet Objective: Provide a controllable dual-flowpath inlet testbed suitable for mode transition research. Includes an inlet performance and operability database.
- Controls Objective: Characterize dynamics and develop a smooth mode transition control through one or more scenarios that maintain propulsion performance.
- Engine Objective: Demonstrate transition with operational engines, (turbine engine is funded).

How will CCE mode transition be done?

- **CCE Mode transition is a time sequence between complex propulsion components. Elements are tied together with controls and large-scale testing in a supersonic wind tunnel.**

- **Propulsion Elements and components**
  - Target Design: M7 TSTO booster stage – non-fuel specific
    - Near term focus on inlet and control through mode transition
    - Mid term: turbine engine
    - Far term: scramjet (currently unfunded)
  - Inlet Designed with 2D tools
    - TechLand M5 SBIR study
    - Interaction with NASA for M7 design, M4 mode transition speeds
    - Small-scale inlet testing
  - Wide range, High Mach turbine integration
    - CCE turbine modified by Williams (WJ-38-15 heritage)
  - Scramjet combustor
    - Original design was rectangular for wide hypersonic Mach range
    - Modified for compatibility with ATK round combustor (reduced cap
  - Nozzle
    - Conceptually compatible with dual flow
    - Focused on turbine exit
    - Spiritech design





Mode transition requires large-scale testing, complex components and controls

When will CCE mode transition be done?

Four+ phases – *three year test program* – cost dictated schedule

(1) Inlet Characterization – *fiscal year ’10.*

Controls research – *fiscal year ’10 / ’11.*

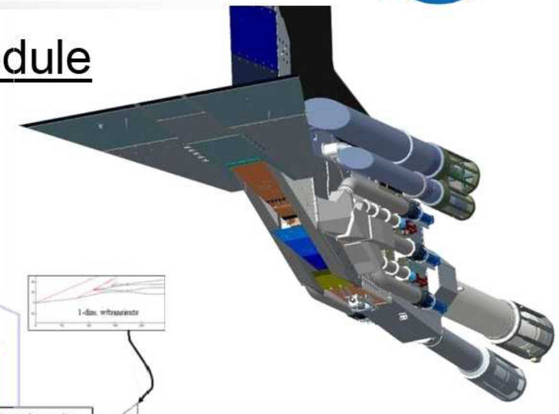
(2) System Identification (SysID)

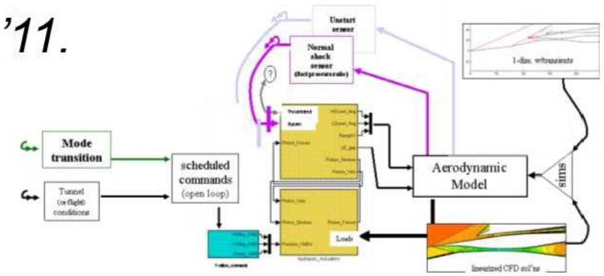
(3) Control Implementation

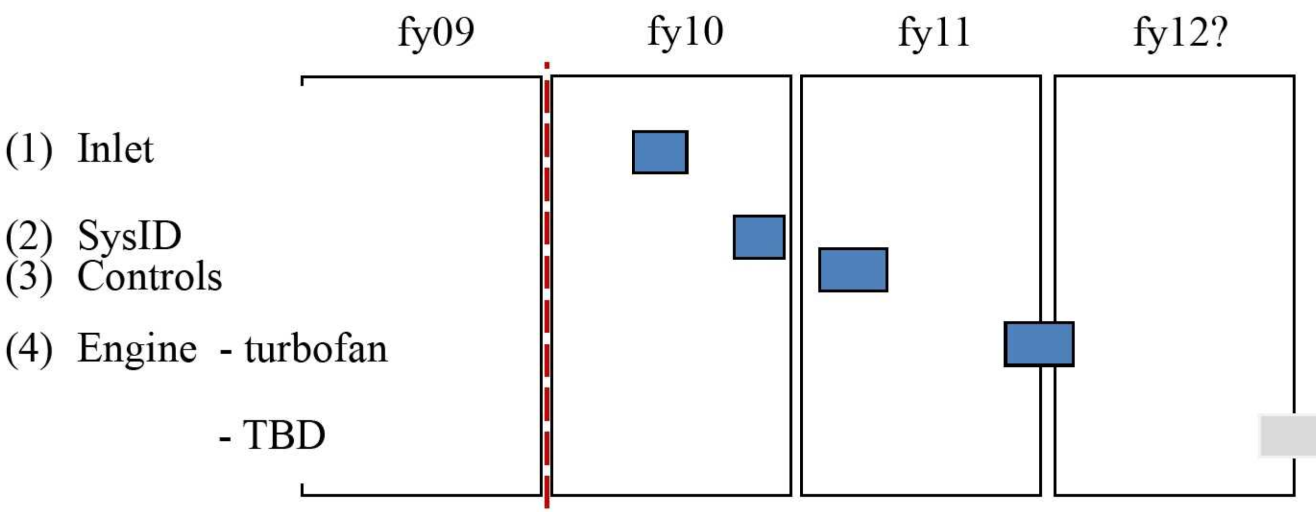
(4) Engine Integration

Turbofan – *fiscal year ’11 / ‘12.*

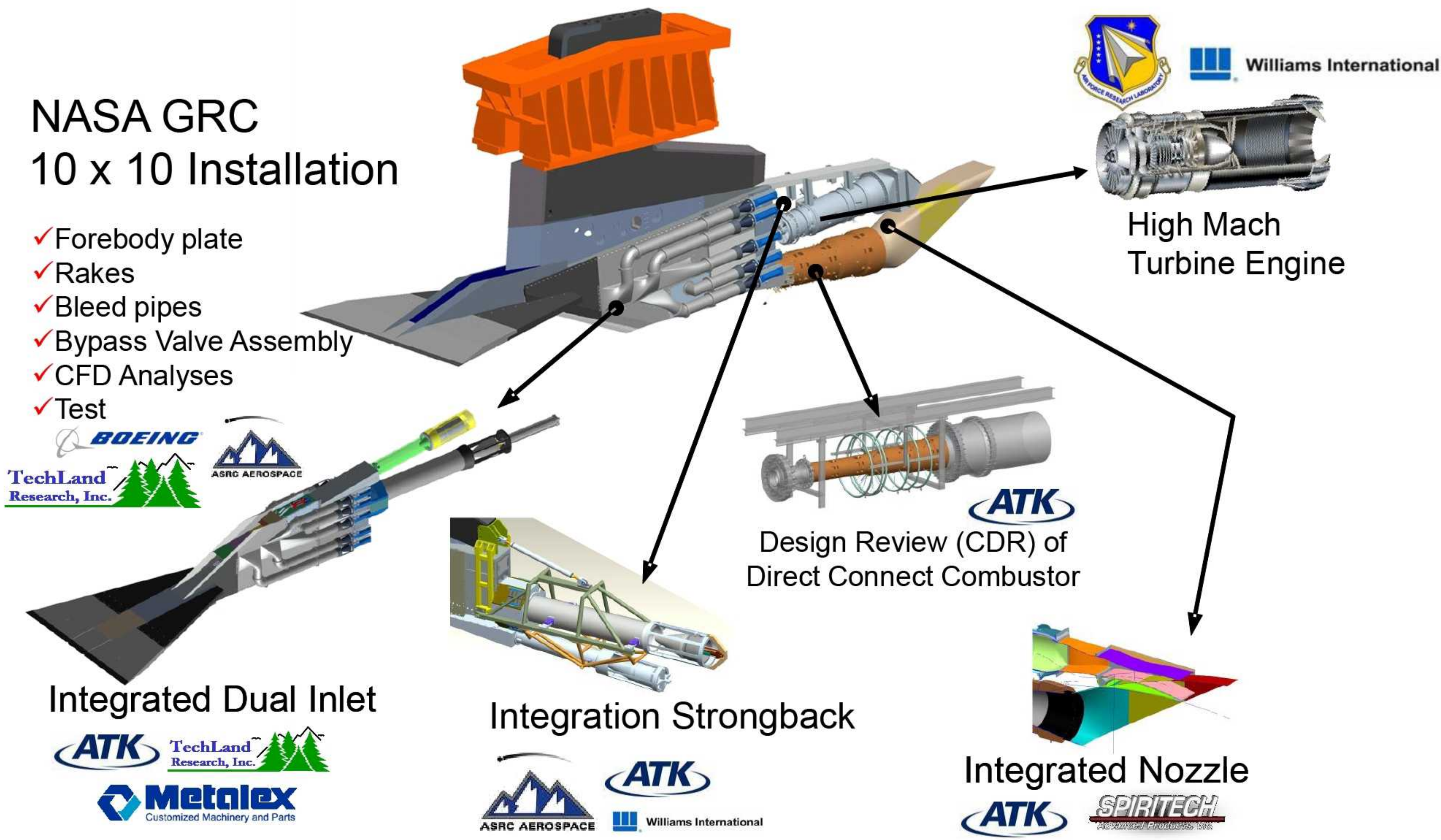
Scramjet integration – *TBD*







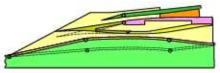
Who: CCE Mode Transition Team



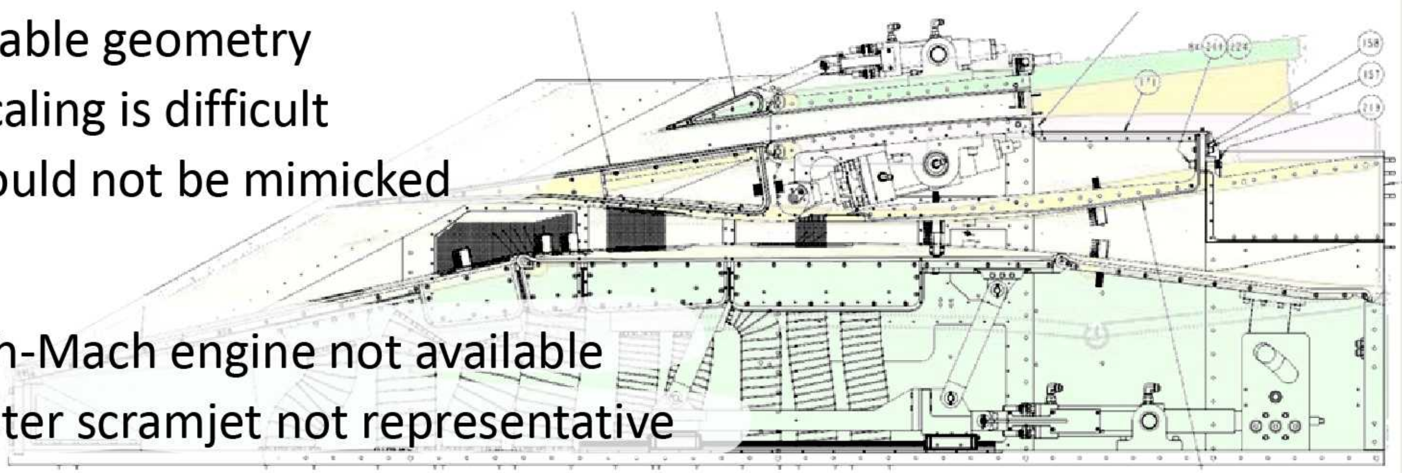
Data reduction will be supported by NASA, NCCCP, and Techland

Why is Large scale testing needed?

- **Inlet: 1x1 SWT 'small-scale' [~1/7th] screening tests are not high quality for performance**
  - Full mechanical geometry not possible
  - Fixed geometry ramps
  - Actuation through sidewalls causes flow leakage
  - Instrumentation limited, (i.e. 1.82" versus 12" Engine diameter)


small-scale

- **Controls: not possible in small-scale**
  - limited dynamic data
  - lack of variable geometry
  - dynamic scaling is difficult
  - volumes could not be mimicked
- **Engine:**
  - 1.821" High-Mach engine not available
  - 1.2" diameter scramjet not representative

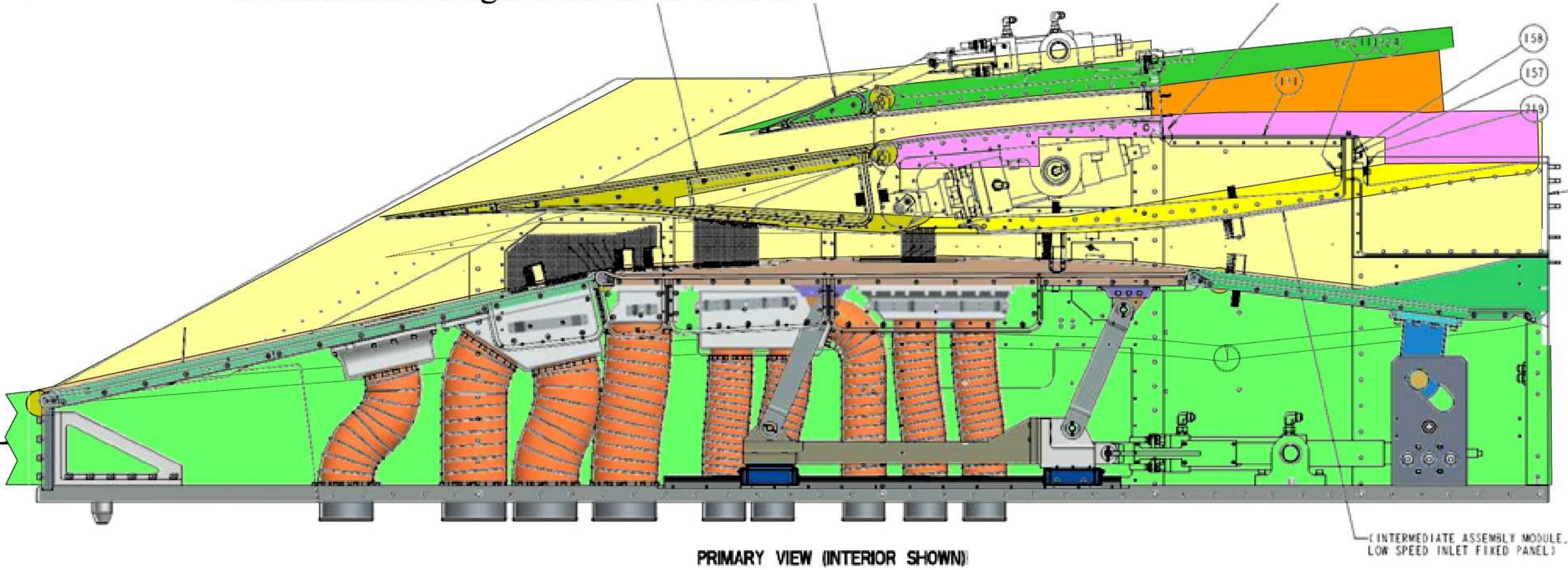
large-scale


Without all elements, mode transition becomes deficient

Why is Large scale testing needed?

Complexity:

- Conceptual / aero. design from Nov. 2006 -- ref. NASA CR-2008-215215, (Techland Research).
- Mechanical Design: ATK as of 4/13/09



- Variable geometry:
  - Rotating low-speed cowl for mode transition
  - Variable Ramp for Mach Range matching
  - Rotating high-speed cowl for Mach range matching
  - Ten bleed compartments, individually metered
  - Angle of attack, coldpipe/plug metering
- Configurations: vortex generators, bleed patterns, sidewalls, controls/engine integration

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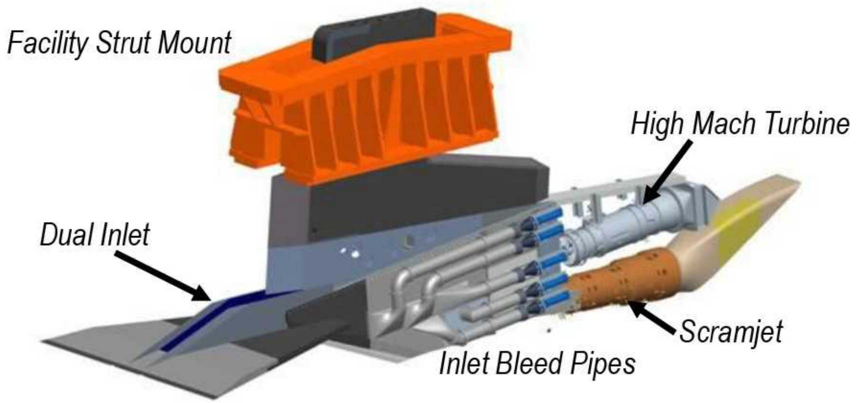
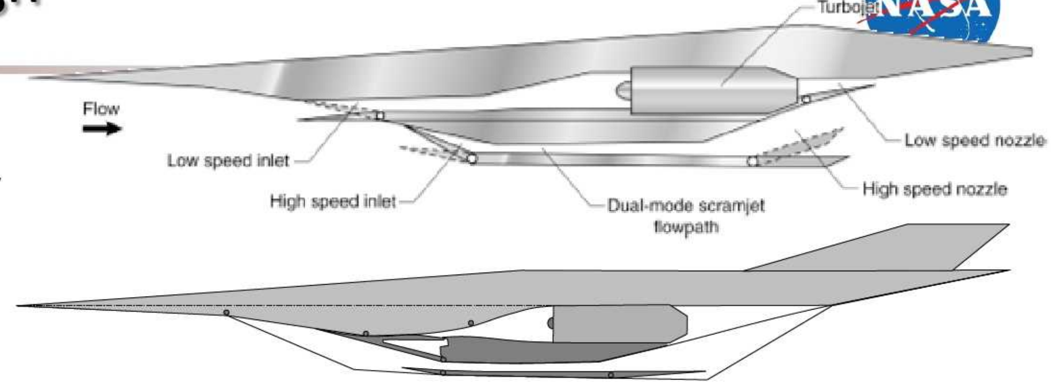
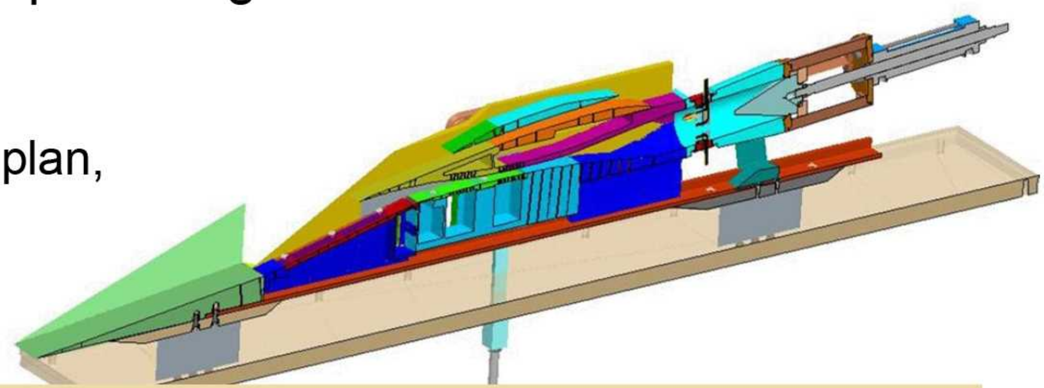


Background: TBCC Inlet Design

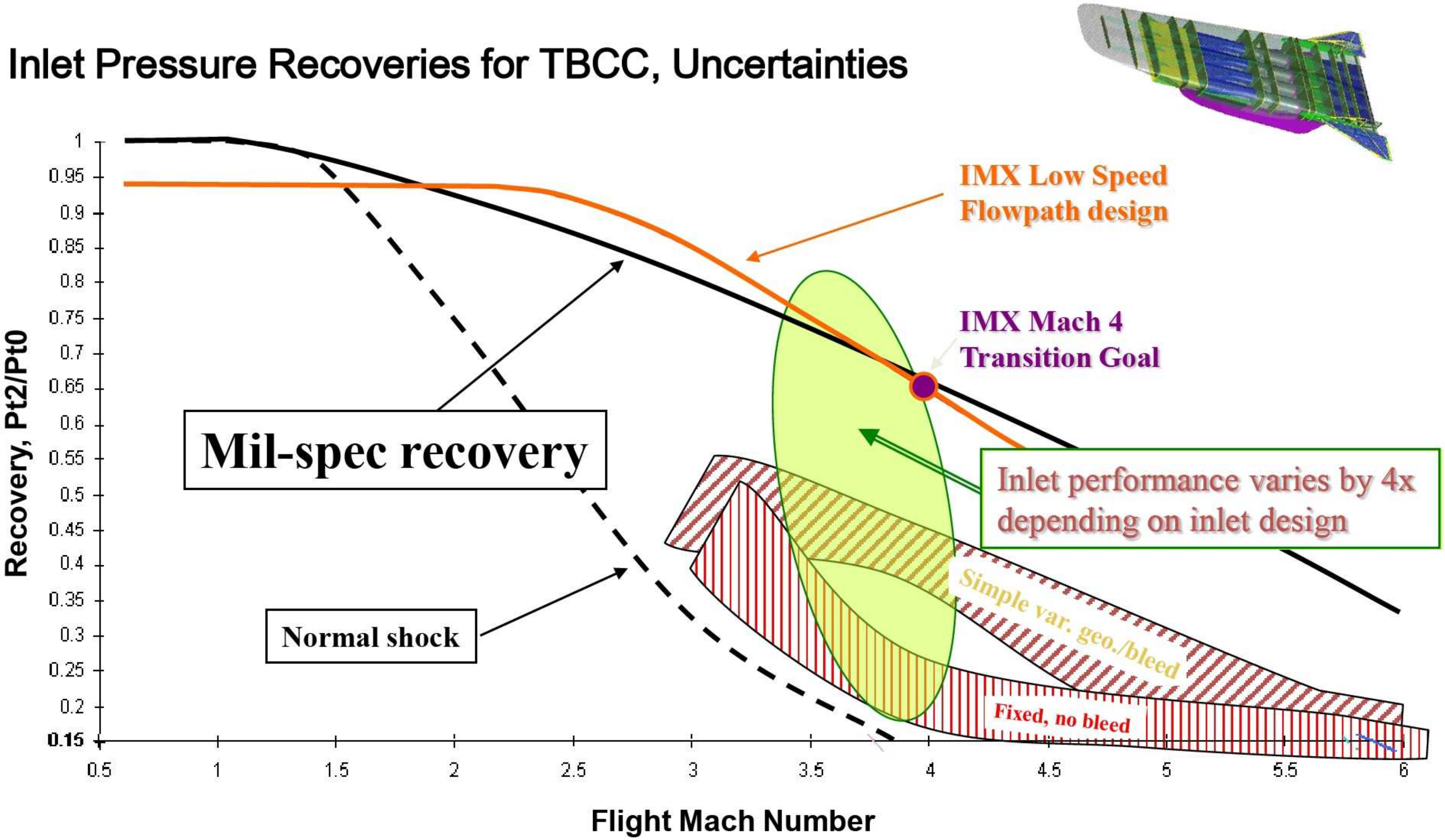


- High-speed: Mach 5 over/under
  - (ref. NASA CR-2004-213122)
  - (ref. Albertson/Emami/Trexler)
- Low-speed: supersonics / mixed comp. / bleed / visc.effect
  - Programs: YF-12 / XB-70 / NASP / SST>HSCT
- Integration: vehicle, turbofan, high-speed flowpath
- Mach 7 Hydrocarbon fueled Scramjet with Mach 4 transition from Turbine
- Historical recoveries / Flow splits / engine demand / mission
- Impact of CFD:
  - Visualize, Instrument, Test plan,
  - Design, Controls
- Small – scale IMX tests



Inlet design driven by TBCC studies, CFD tools, and physical constraints

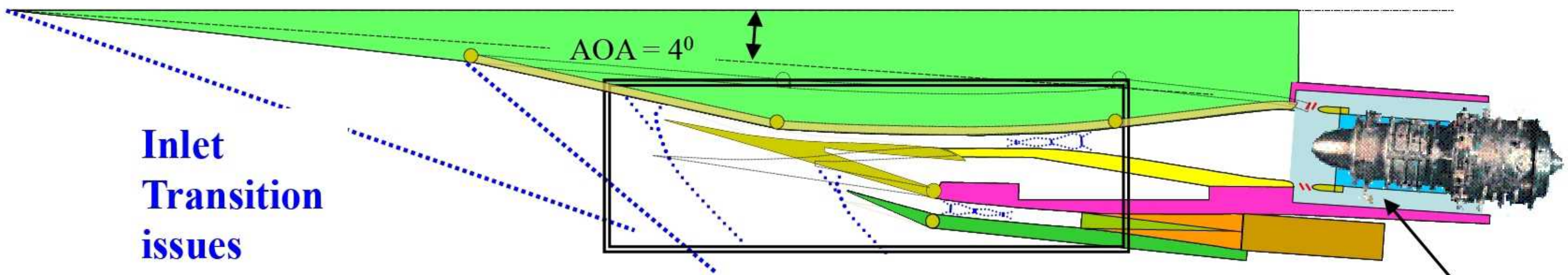
Background: Inlet performance



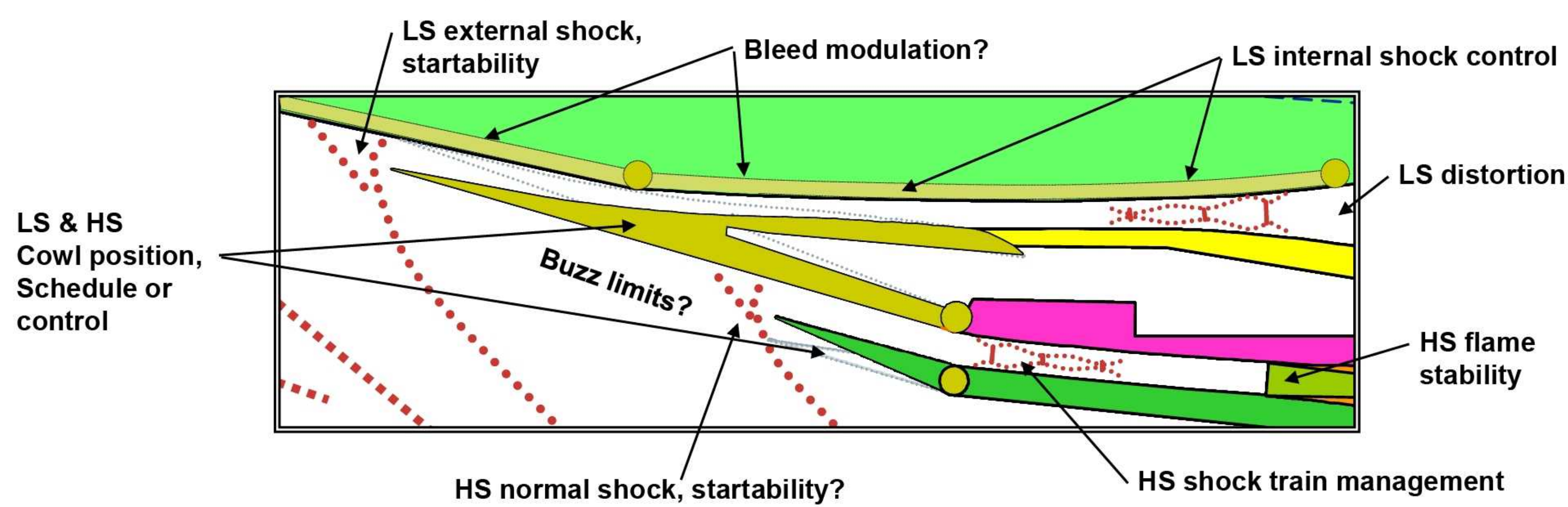
Mil-spec recovery is high performance and requires inlet complexity

Inlet design: requirements for Mode Transition & Wide Mach range

Inlet design driven to complexity: Variable ramp, rotating cowls (2), and bleed compartments (9)



Mode transition sequences: *Mach 4 shock scenarios*

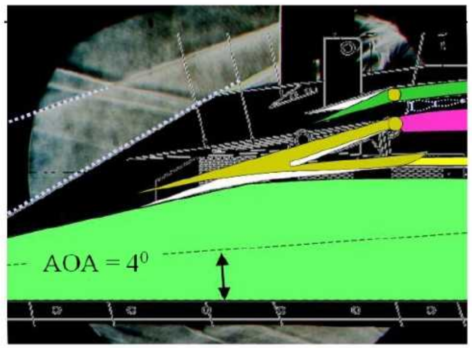


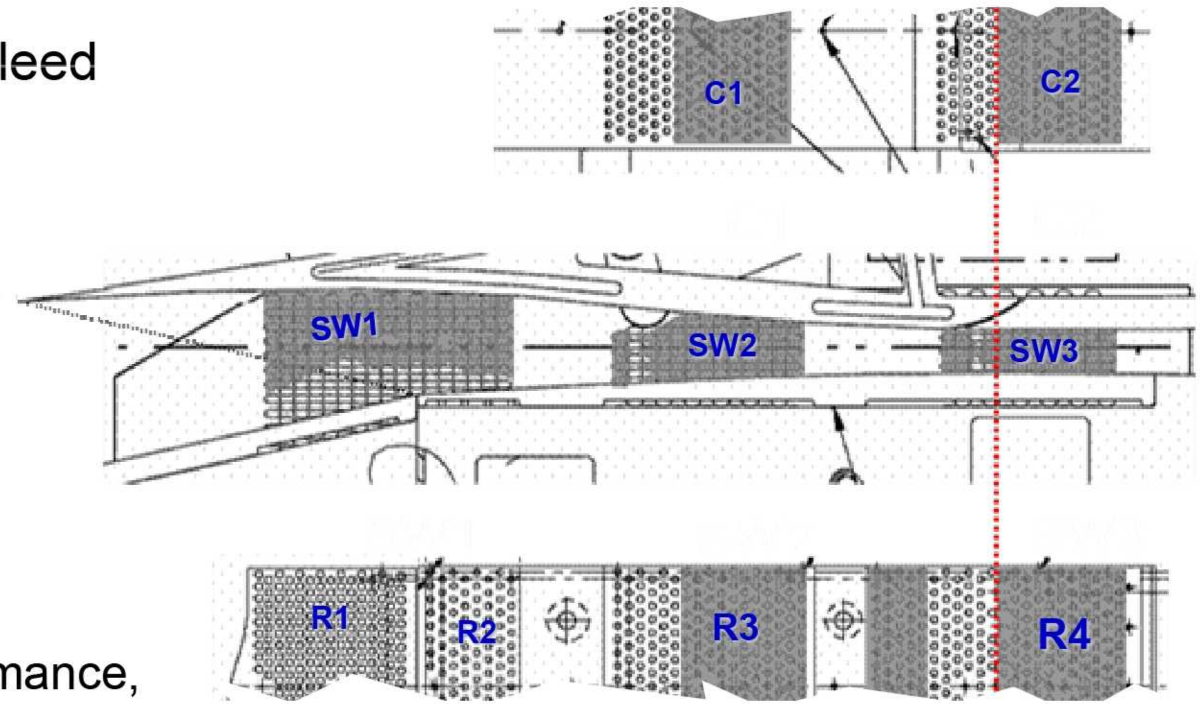
Mode transition design at Mach 4 has complex interactions

1x1 SWT screening results, 69 runs in two phases

- Results discussed in JANNAF report,
  "Inlet Mode Transition Screening Test for a TBCC propulsion system", Boston, 2008

- Configurations / bleed



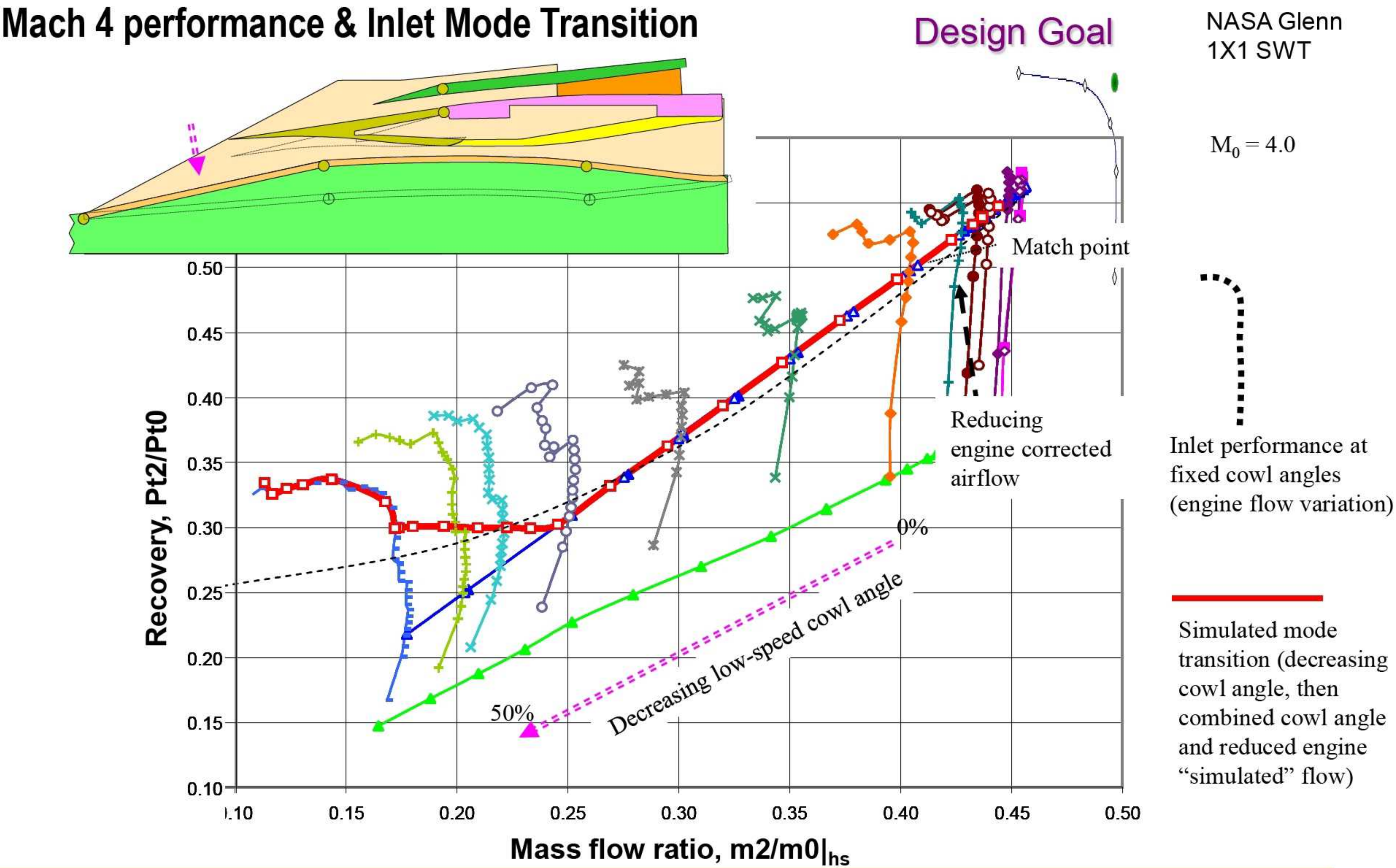


- M4 results:
  good performance,
  popping behavior,
  distortion,
  Mode-transition (mode-x)

- Off-design results: recovery

1x1 experiment completed, inlet design has high performance for mode-x

1x1 SWT screening results: mode-x scenario



Mach 4 performance is near design goal: mode transition is smooth

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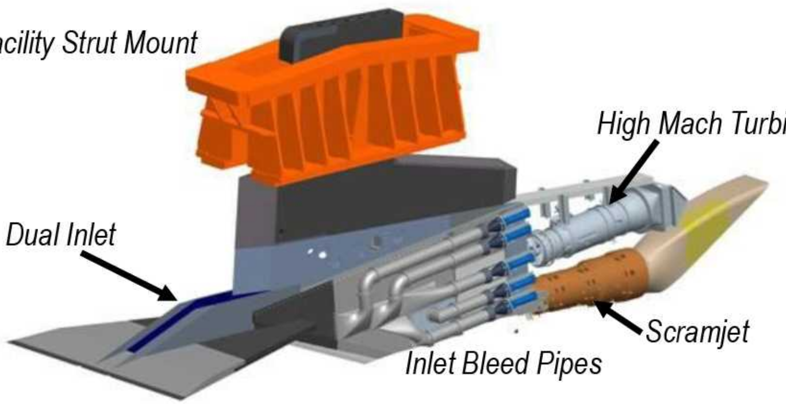


Overview of CFD Effort from last year's FAP meeting

Objectives

- Provide analysis support of ground testing of the TBCC Inlet Mode Transition (IMX) concept.
- Enhance the understanding of the aerodynamics of inlet mode transition.
- Continue development of CFD tools for high-speed inlet analysis.

IMX-Small-Scale 1x1 SWT CFD Simulations

- Provided estimates of performance, flowfield visualization, and porous bleed characteristics prior and during the 1x1 SWT testing in 2007 (Lee, Slater, and Dippold).
- ➢ **Post-test analysis of 1x1 SWT data (Run 35) to illustrate the flowfield and validate Wind-US CFD methods (Slater).**
- Post-test analysis of 1x1SWT data (Run 35) to validate BCFD (Boeing).

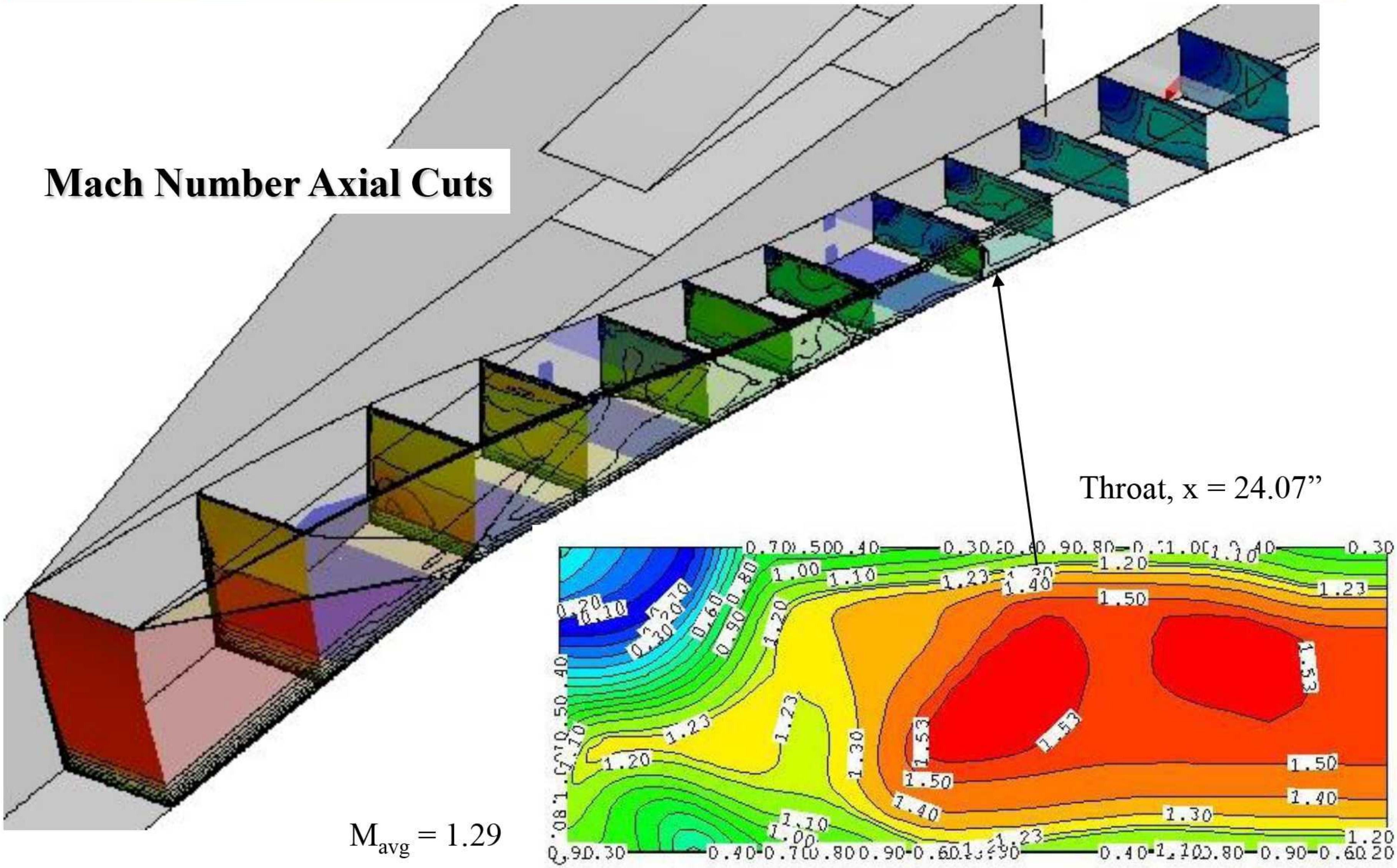
IMX-Large-Scale 10x10 SWT CFD Simulations

- Pre-test analysis of portions of the test matrix to provide visualization of the flowfield, estimations of performance, and effectiveness of porous bleed (Boeing).
- ➢ **Pre-test analysis of the high-speed flowpath and isolator performance (Dippold).**
- Estimation of flowfield sensitivities with respect to variations in low-speed ramp angle and back-pressure for development of inlet controls (Slater, Boeing).

CFD studies highlighted in bold are those discussed at last FAP meeting…

CFD highlights flow features that can guide hardware options and test planning

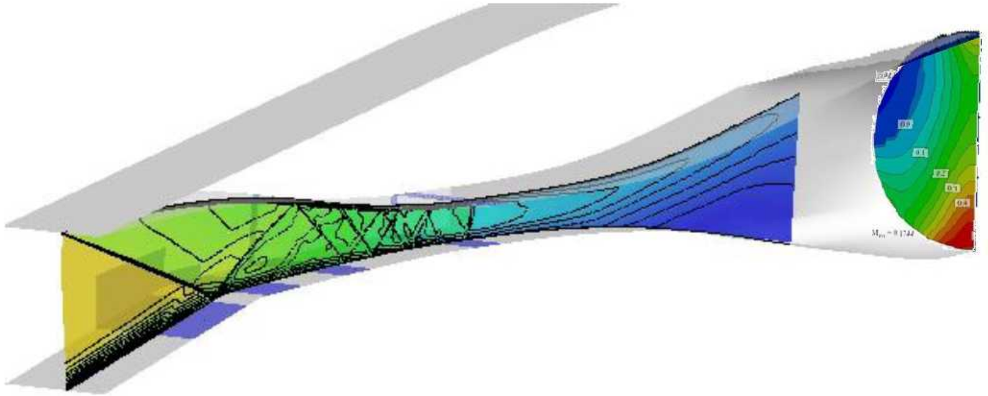
Low – speed flowpath CFD (Slater)

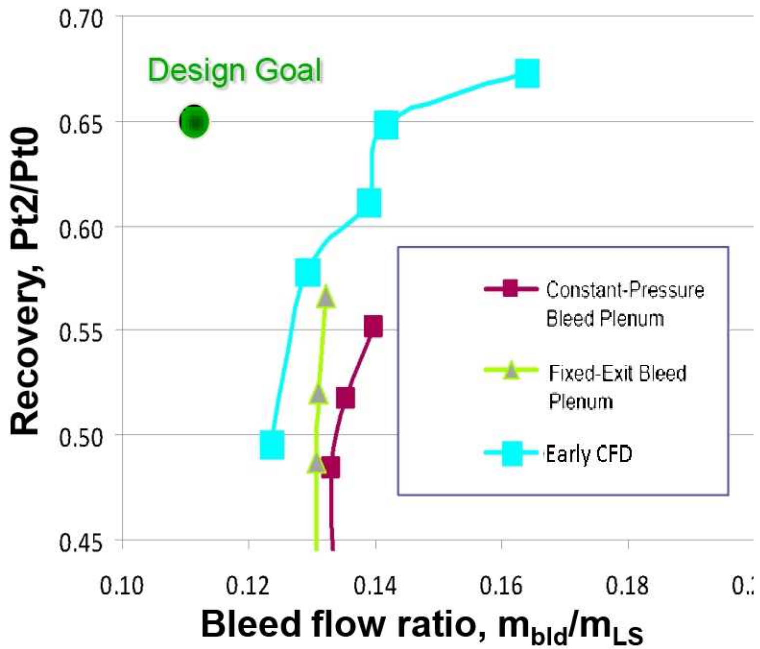


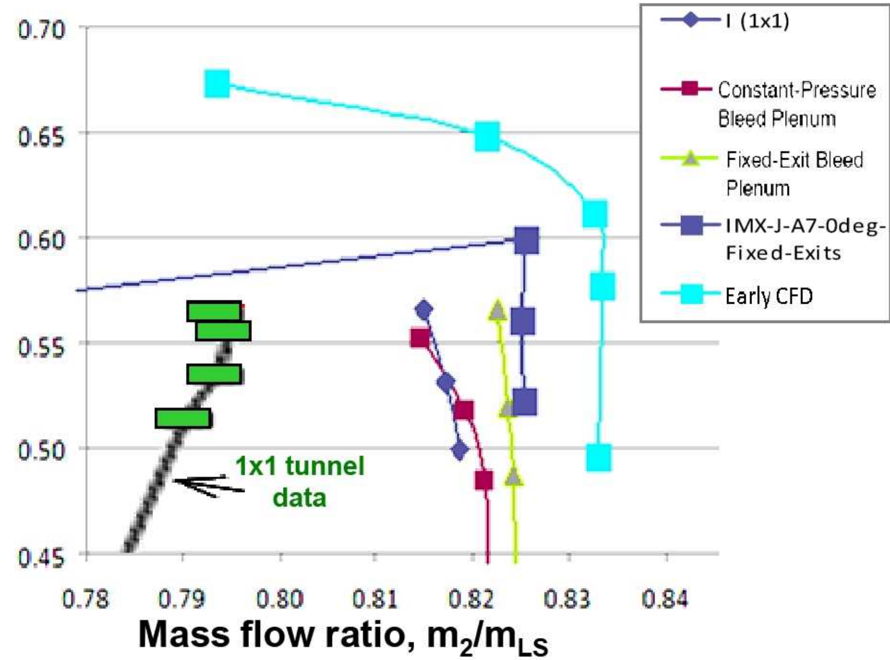
John Slater and Vance Dippold lead NASA CFD analyses

Back-pressured CFD Study: Performance 'Cane' Curves

- Low-Speed Inlet Performance
- 1x1 SWT Run 21 bleed configurations
- Distortion from CFD is high
- New modeling for bleed plenum b.c.'s
- Bleed A7 seems best for LIMX



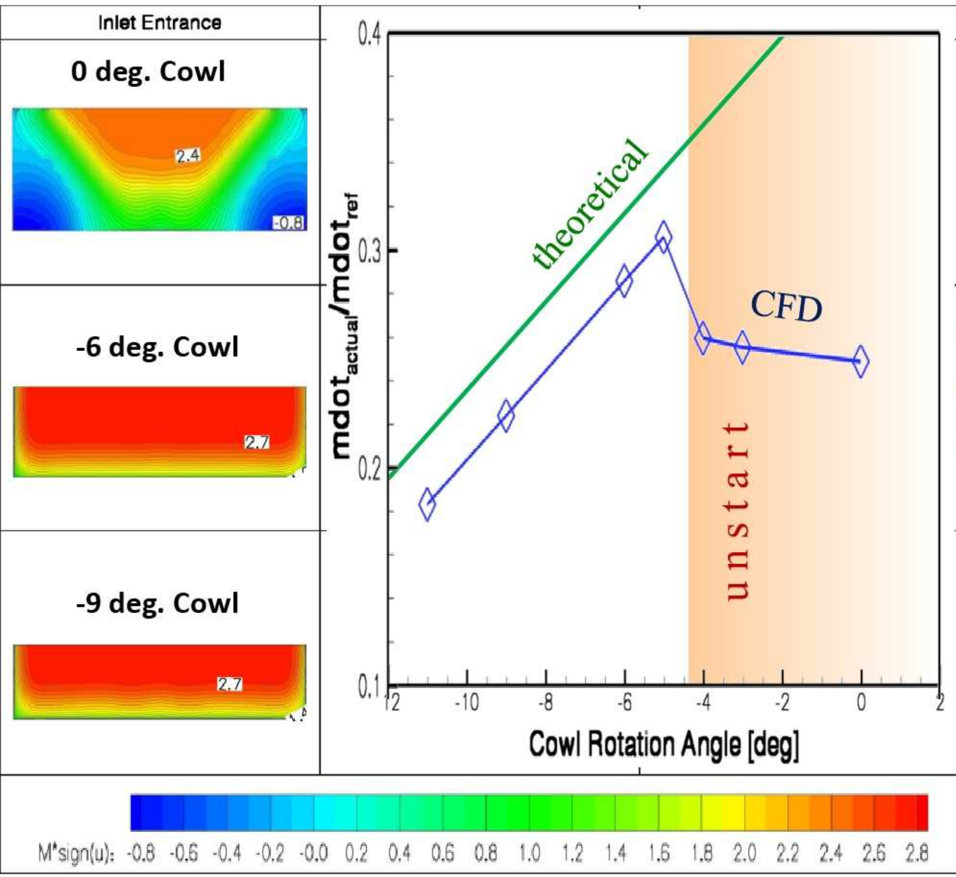


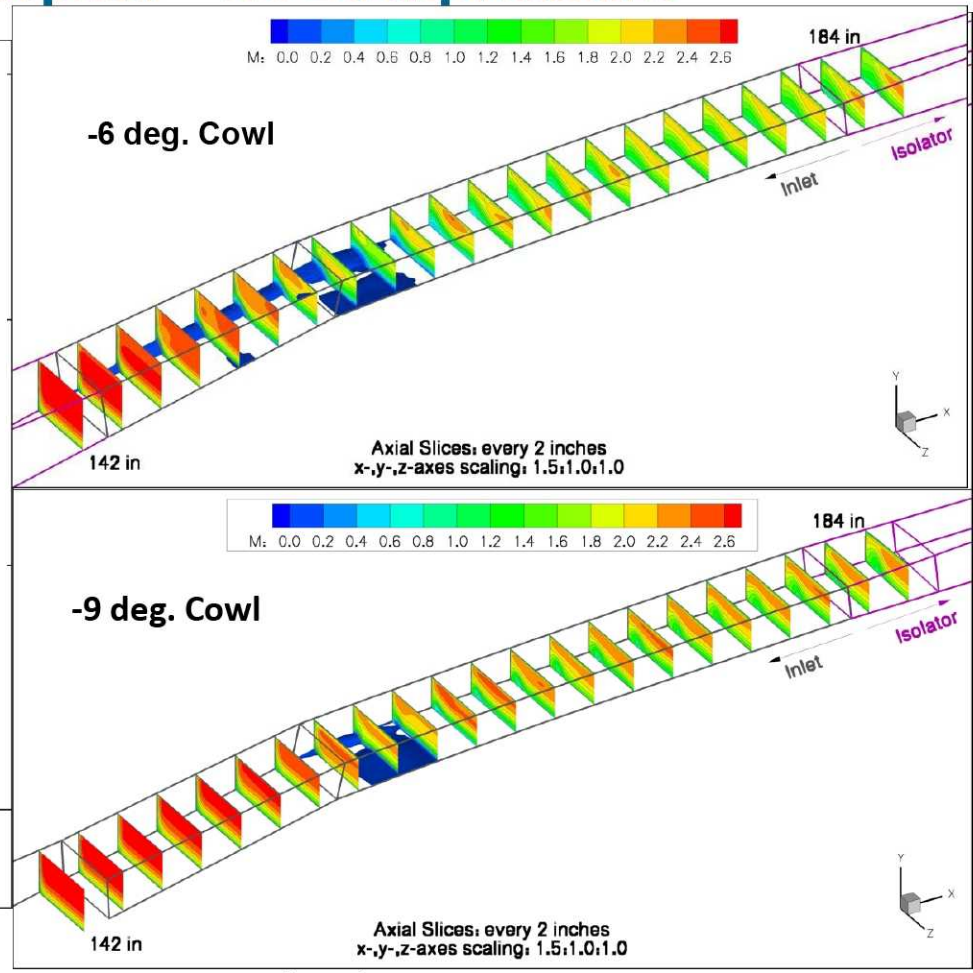


CFD suggests LS recovery perf. is near goal, AIAA being prepared 2009_09_28_

High speed flowpath, Cowl Rotation (Dippold)
Low-speed closed

Mach Contours Through HS Flowpath - No Backpressure

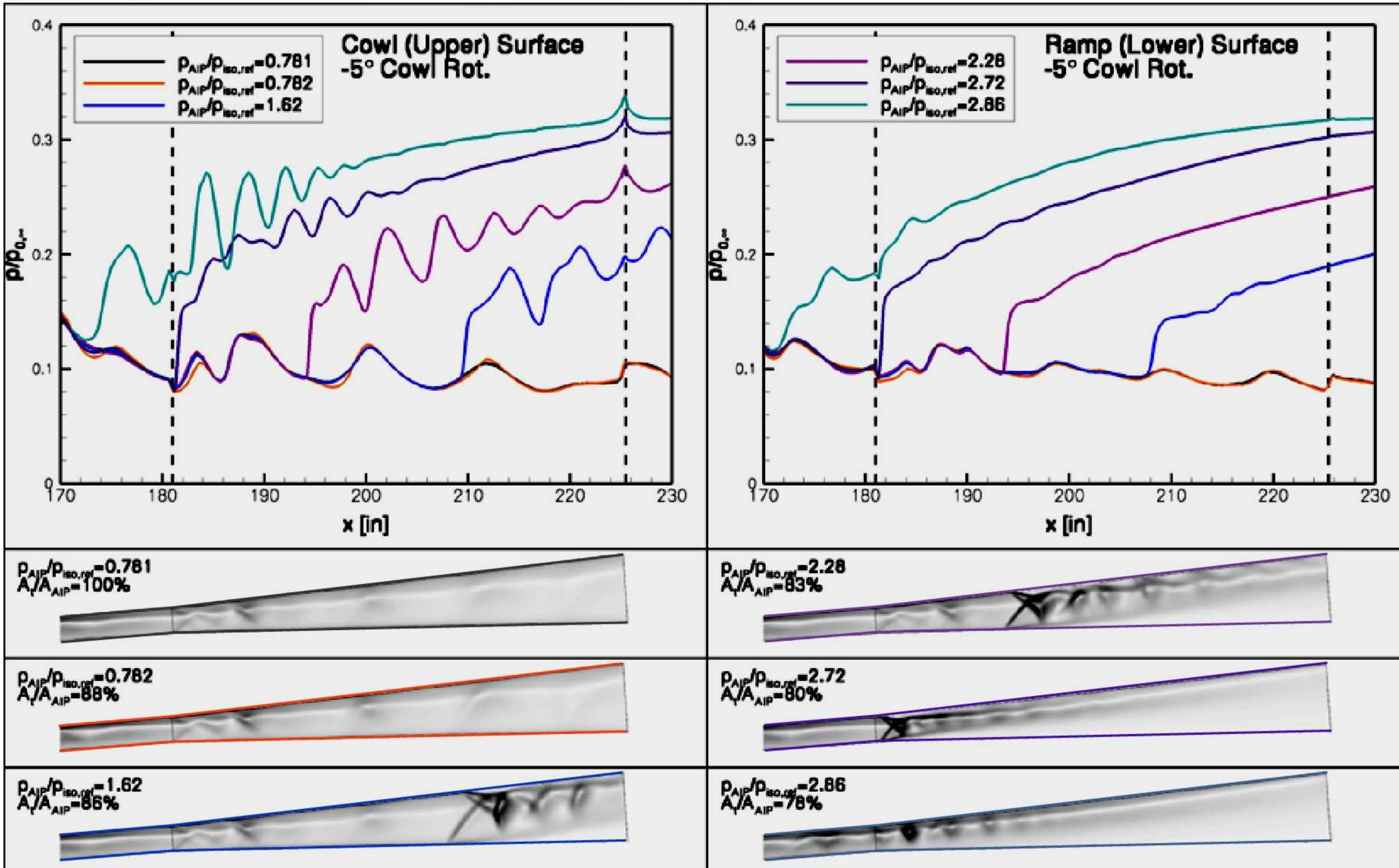




- Significant corner flow separation observed for +2 to -6 HS cowl angles
- Minor flow separation observed for -9 and -11 HS cowl rotation angles

HS CFD suggest strong 3D effects, and unstart around -5 deg.

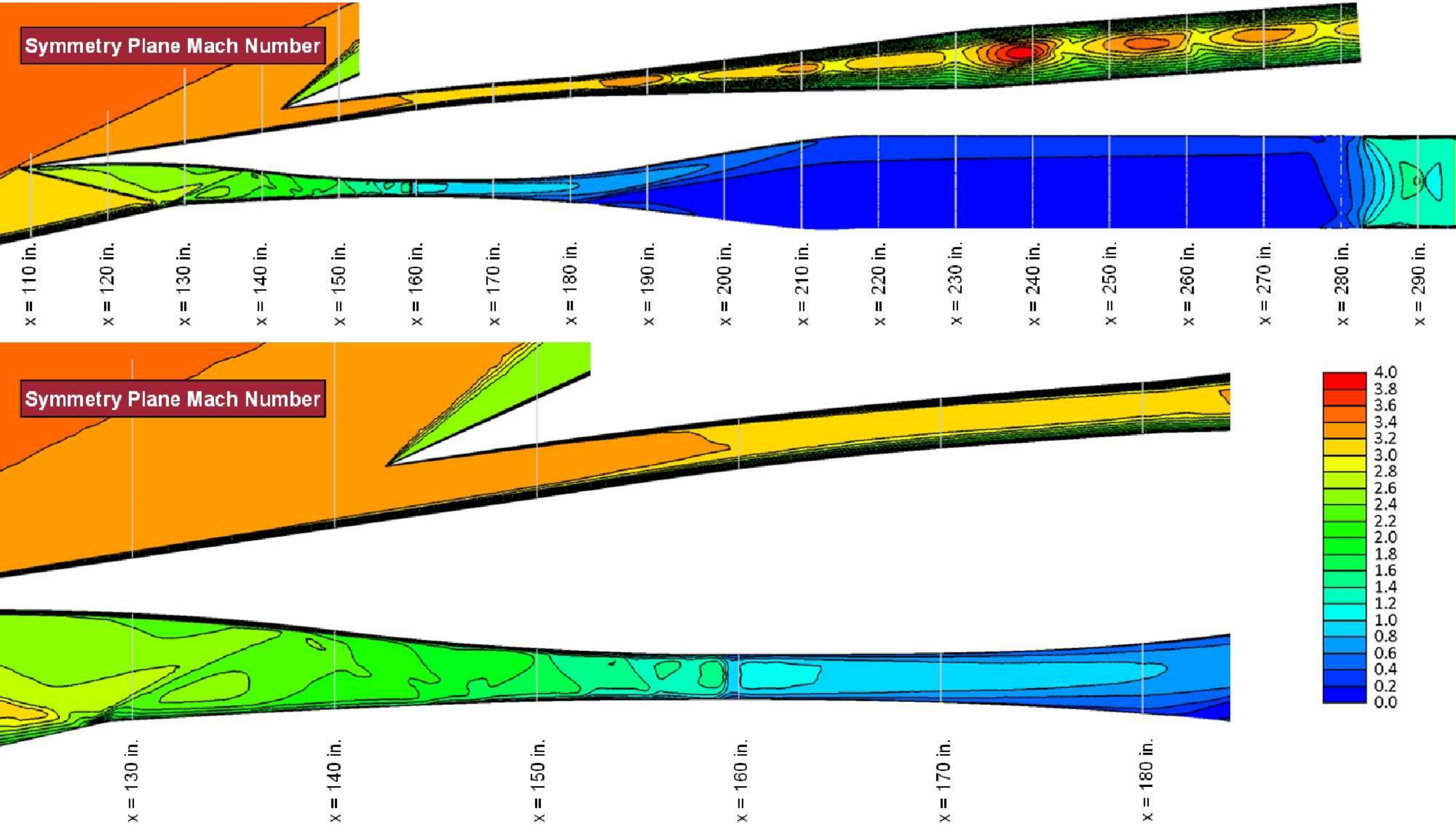
High speed flowpath (Dippold)
Surface Pressure and Schlieren Plots: -5° Cowl



- Dashed vertical lines denote isolator region

Sample of Boeing's CFD for CCE-LIMX

Case 018_173_041.17 - LS Cowl Angle = 0.4°; HS Cowl Angle = 0°; Ramp Angle = 12.5°



David Witte coordinates Boeing's CFD efforts

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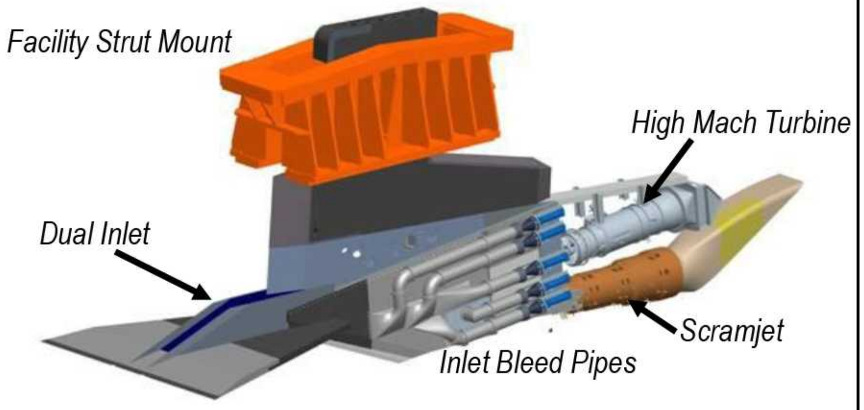


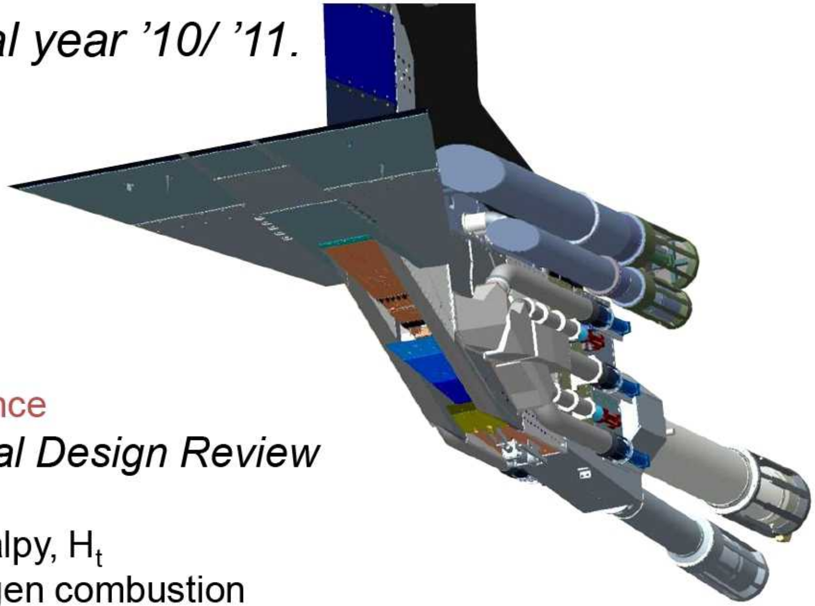
CCE Mode-X: overall test plan

Four+ phases – *three year test program* – cost dictated schedule

1. Inlet Characterization – *fiscal year '10.*
   - Performance at Mach 4 and 3 design points
   - off-design mapping (Mach and Angle-of-attack)
   - inlet mode transitions scenarios
   - simulated engine mode transition sequences

Controls research and development – *fiscal year '10/ '11.*

2. System Identification of inlet dynamics
3. Controls development and implementation



4. Engine Integration
   - Turbojet – *fiscal year '11 / '12.*
     - Limited life WI bypass turbojet
     - Representative mode transition sequence
   - Scramjet integration – *funded through Critical Design Review*
     - Fabrication and Testing are Unfunded
     - Tunnel dynamic pressure, q, and enthalpy, H_t
       - covers lower envelope for hydrogen combustion
       - Requires tunnel enhancements for higher q, H_t typical of endothermic hydrocarbons

A methodical approach that maps a course towards CCE Mode transition

CCE Mode-X: Possible scenarios

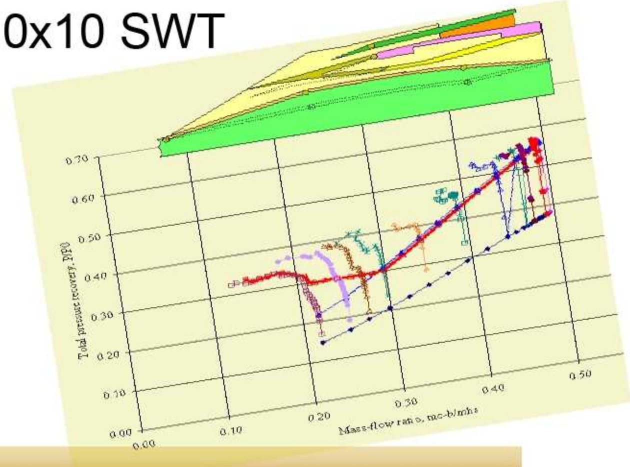
Inlet Characterization – simulated engine mode transition sequences

- Small-scale inlet test indicates:
  - Well behaved turbine flow characteristic during splitter cowl reduction.
  - Distortion and high-speed inlet operability await Large-scale tests.

- Time frame for mode transition and sequences will be investigated
  Inlet transient timed to:
    - Turbine spool down: (balanced thrust transient)
    - Turbine inlet ‘slammed shut’: (thrust transient causes pinch)
    - Turbine synced for acceleration: (excess thrust transient)
    - High-speed flowpath operability constraints?

- Other transient effects that can be investigated in 10x10 SWT
  - Angle of attack changes, (low frequency)
  - Mach number changes, (low frequency)

- Understand inlet dynamics for basic inlet control
  - Normal shock / bypass
  - Bleed/cowl/ramp scheduling
  - Restart control, (lower priority)

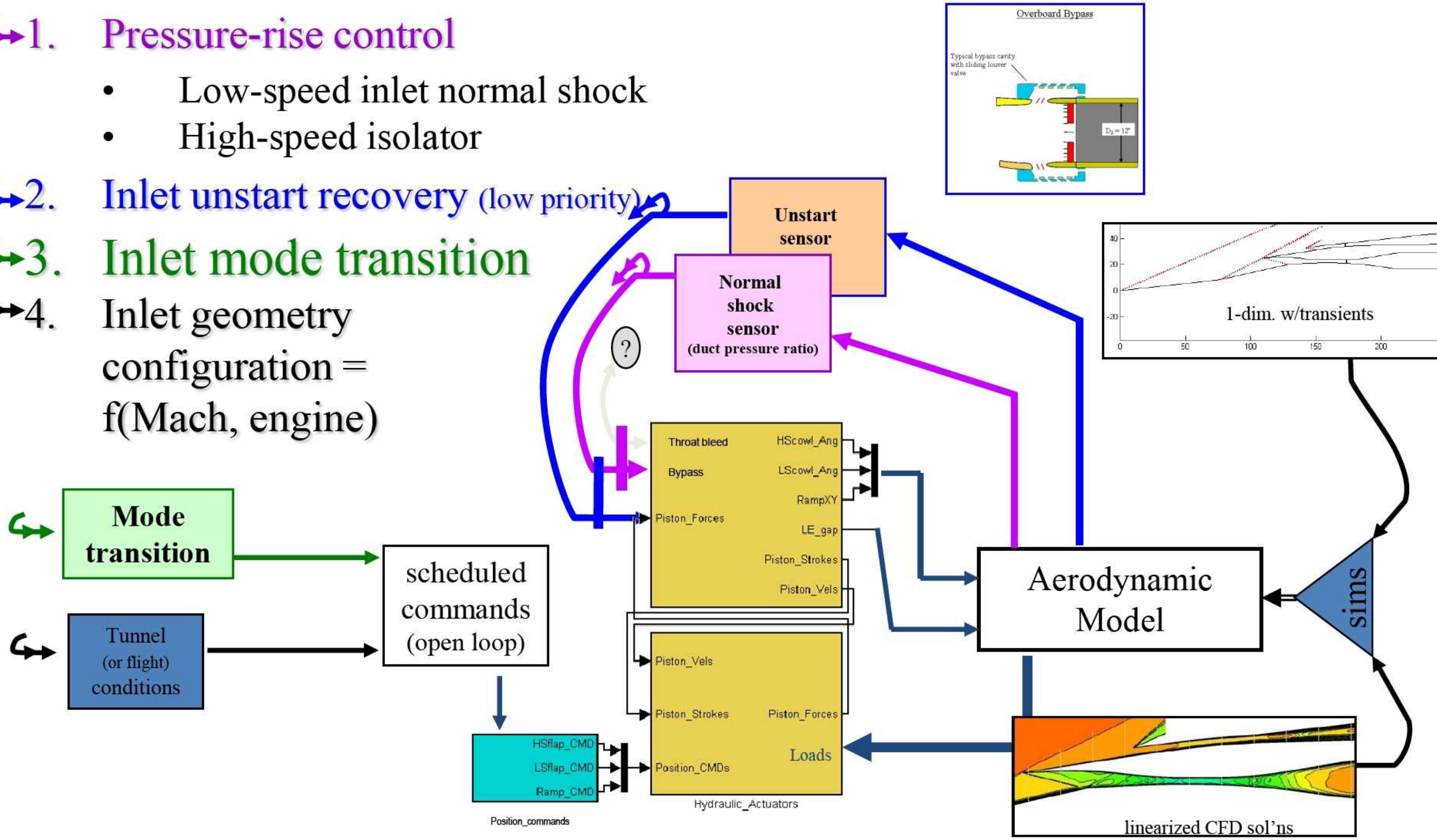


Detailed planning for mode transition scenarios has begun

Controls Tests for Inlet Mode Transition

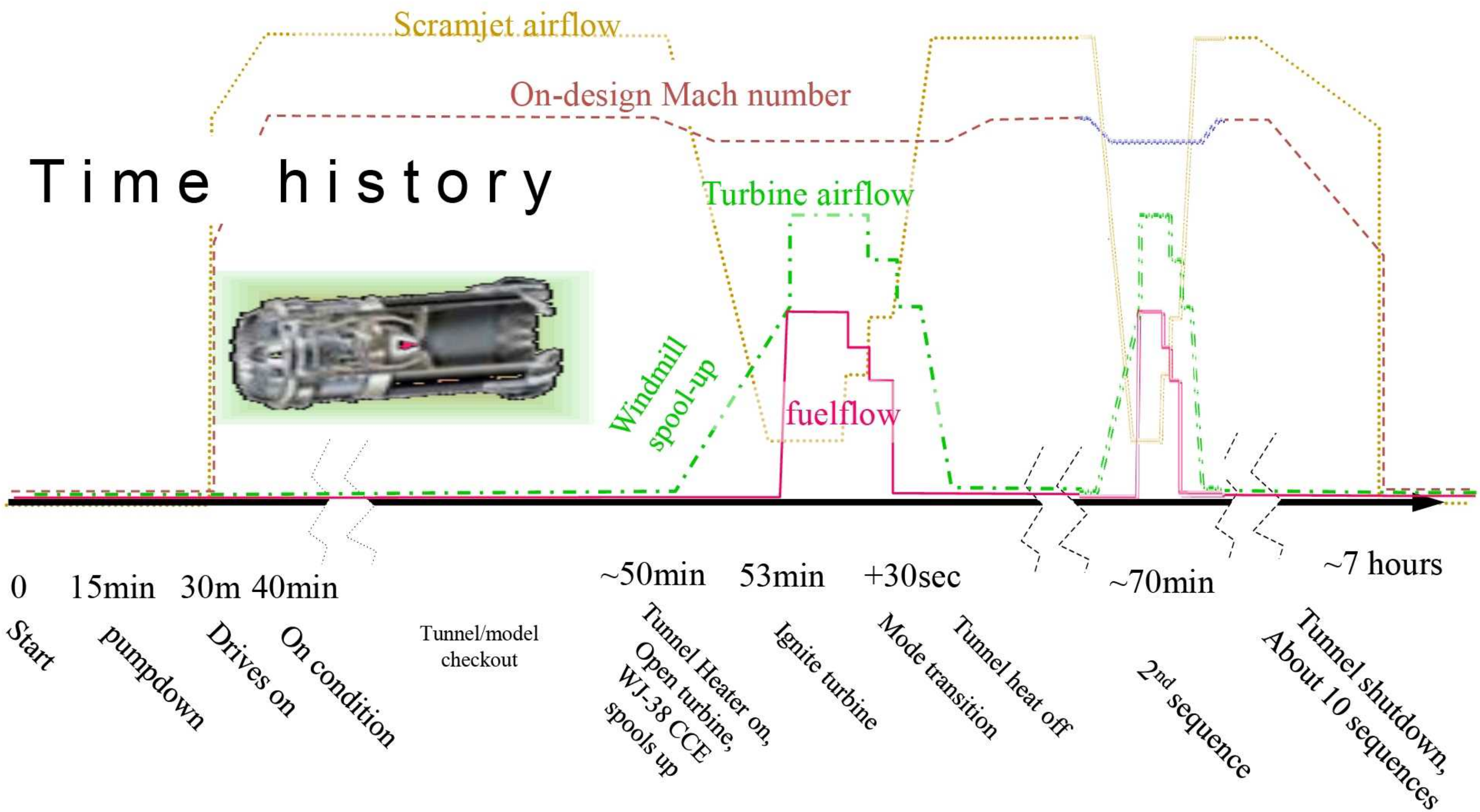
Control composed of four loops: [listed from inner to outer]

1. Pressure-rise control
   - Low-speed inlet normal shock
   - High-speed isolator
2. Inlet unstart recovery (low priority)
3. Inlet mode transition
4. Inlet geometry configuration = f(Mach, engine)



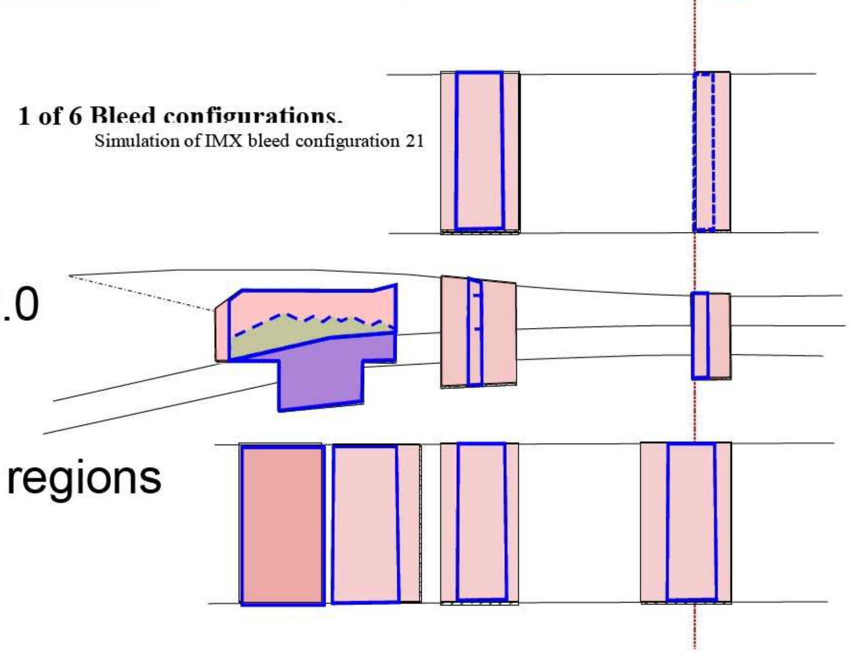
CCE Mode-X: A typical tunnel run

Turbojet Engine Integration -- Representative mode transition sequence



A typical time history shows the flexibility of 10x10 for turbine testing

CCE Mode-X: inlet test plan

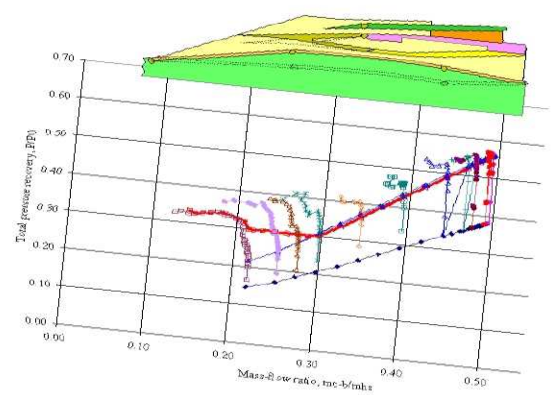


<u>Test configurations – 6</u>

- Mode transition at Mach 4
- Mode transition at Mach 3.1
- Inlet performance at Mach 4, 3.5, 3.0, 2.5, 2.0

1. All bleed open
   - Develop bleed characteristics for bleed regions
2. All bleed open, closed forward SW1 bleed
   - 3 vortex generator configurations
   - Constant bleed plenum pressure
3. Reduced bleed configuration
4. Cowl bleed only
5. No bleed

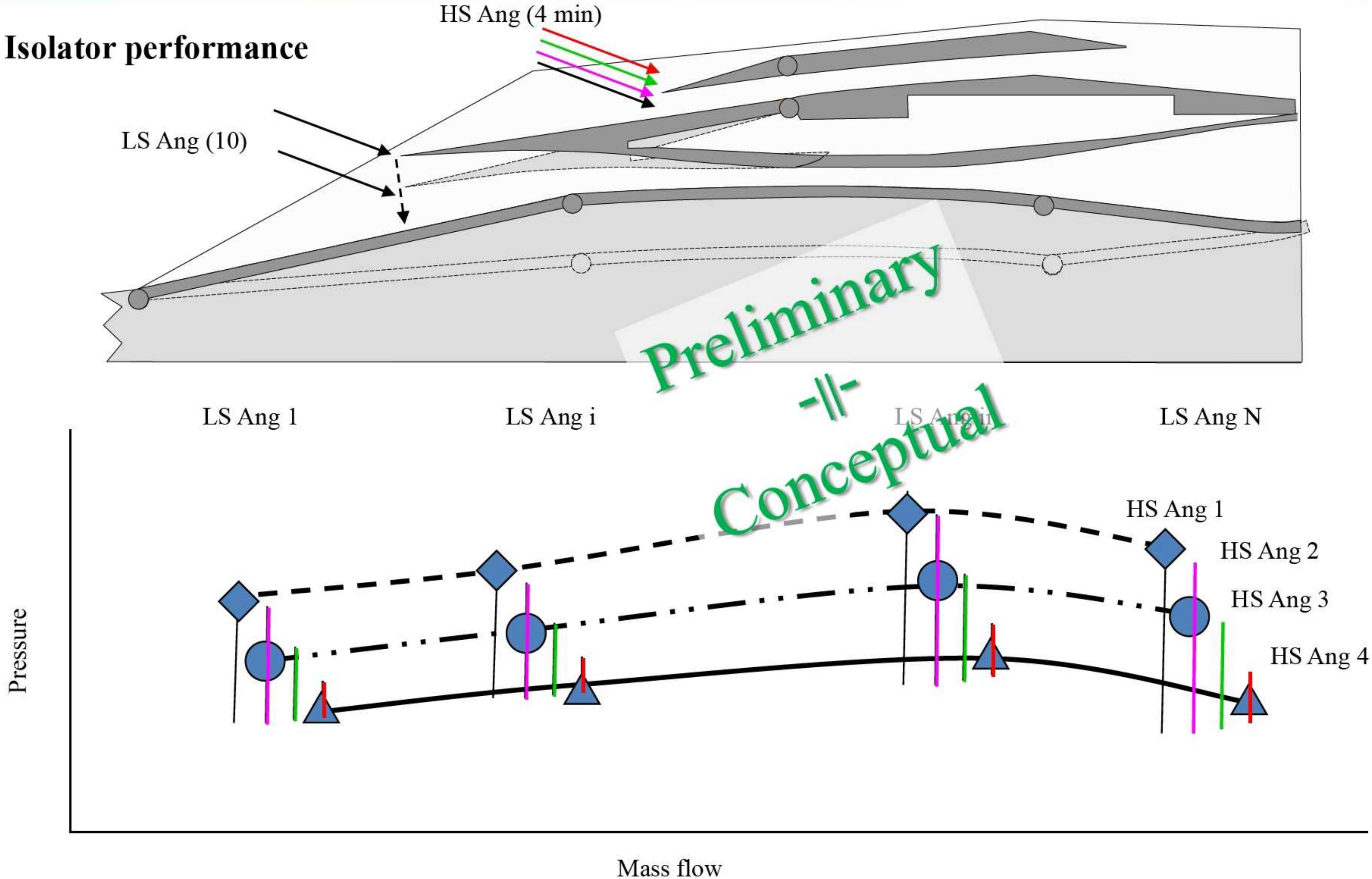
6. Cowl lip variations



➢ **HS flowpath performance at select LS config.**

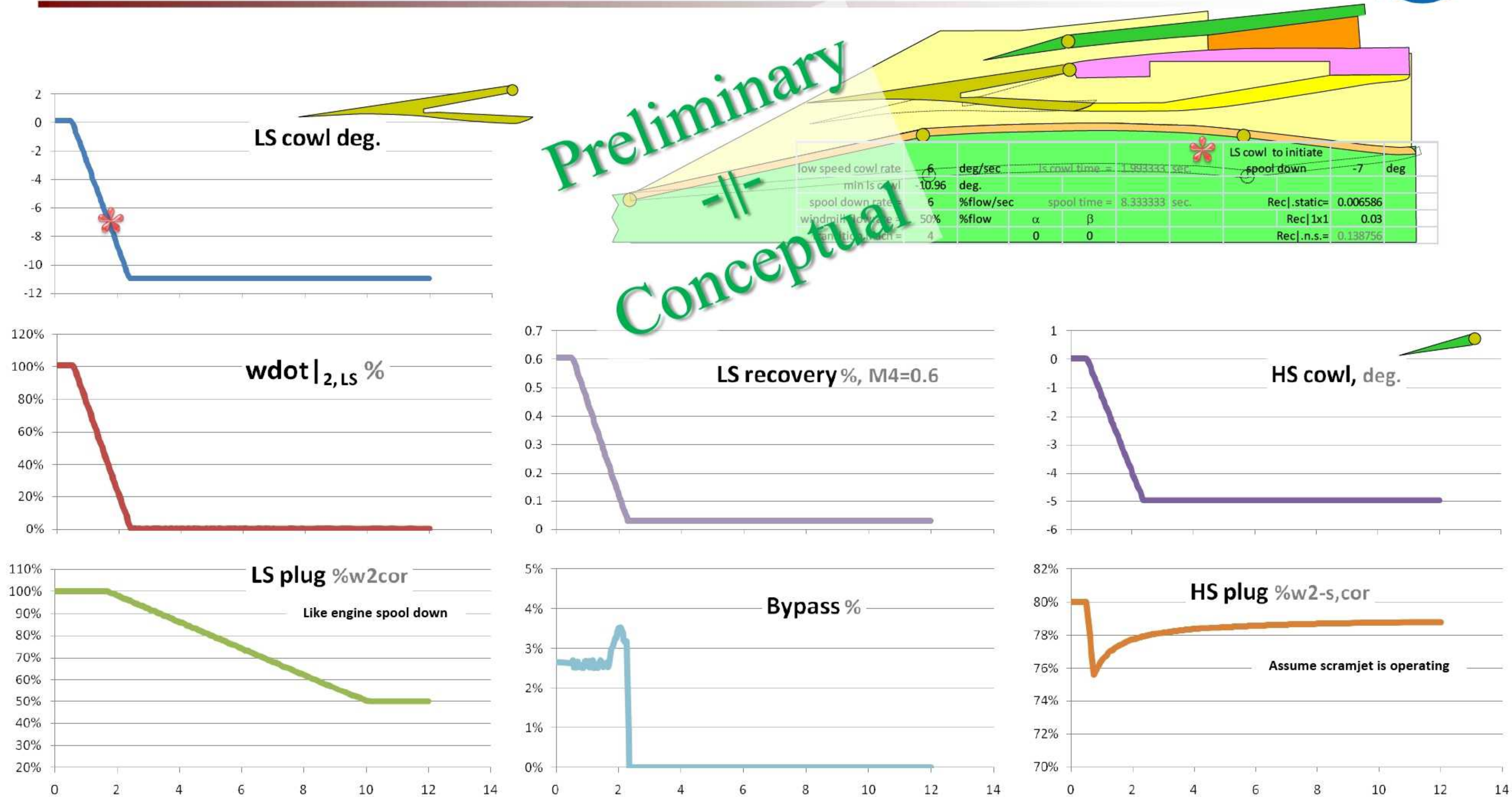
An Inlet test plan has been drafted for operational discussion

CCE Mode-X: HS inlet scenario



High-speed inlet transition is unknown until the Large-scale testing begins

CCE Mode-X: Sample inlet time sequence



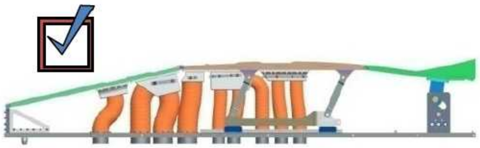
time, seconds

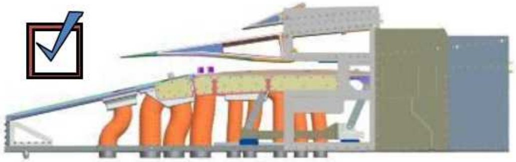
Various sequences can be explored to understand mode transition

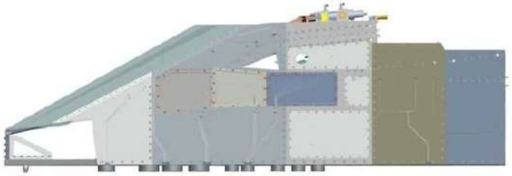
CCE Mode-X: Inlet Milestone

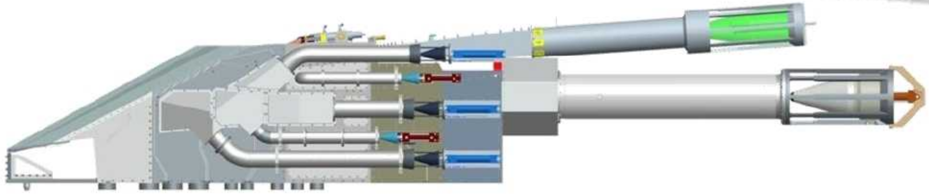
HYP.07.02.001 GRC/RTE: Inlet: Large scale (L-IMX) experiment to demonstrate mode transition. FY10 (!March, 2010)

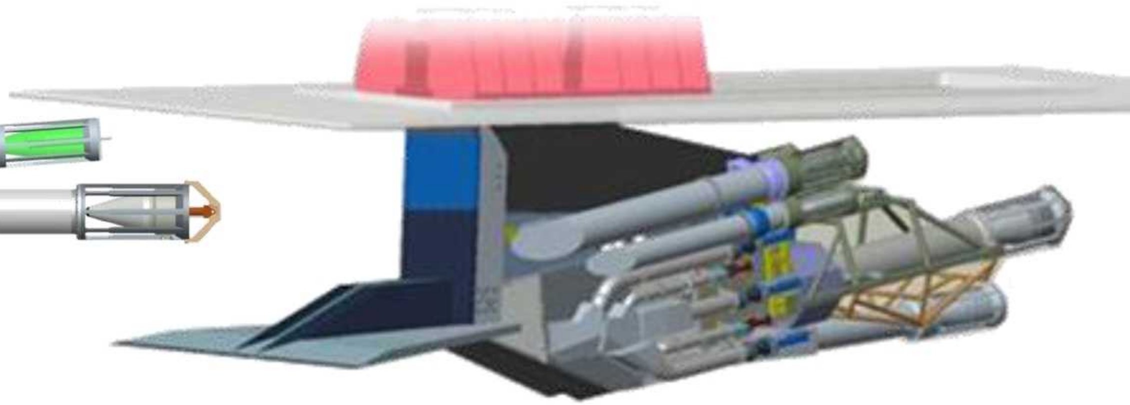
- additional time required for design/fab of the model has delayed testing.







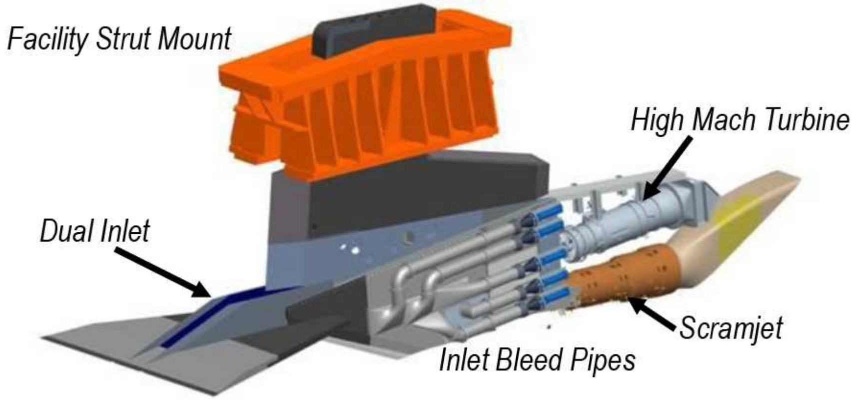




Hardware delivery delayed due to ramp actuation redesign

Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, why, how, when, who?
- Research Objectives
- Inlet Design / small-scale test results
- CFD predictions
- Test Planning
- Instrumentation
- Summary



CCE Mode-X: inlet instrumentation

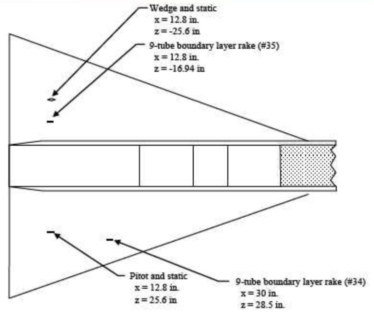
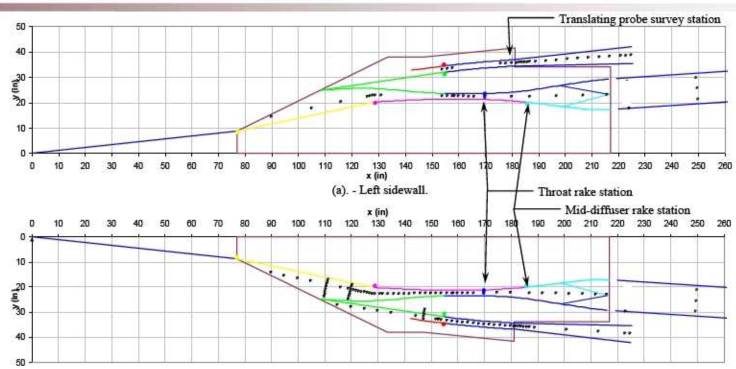
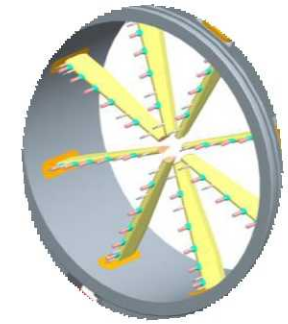


Figure 73A. - Sketch indicating locations of existing outboard Mach 5 Inlet expansion plate instrumentation.



(b). - Right sidewall.

Figure 58 – Sidewall surface static pressure instrumentation.



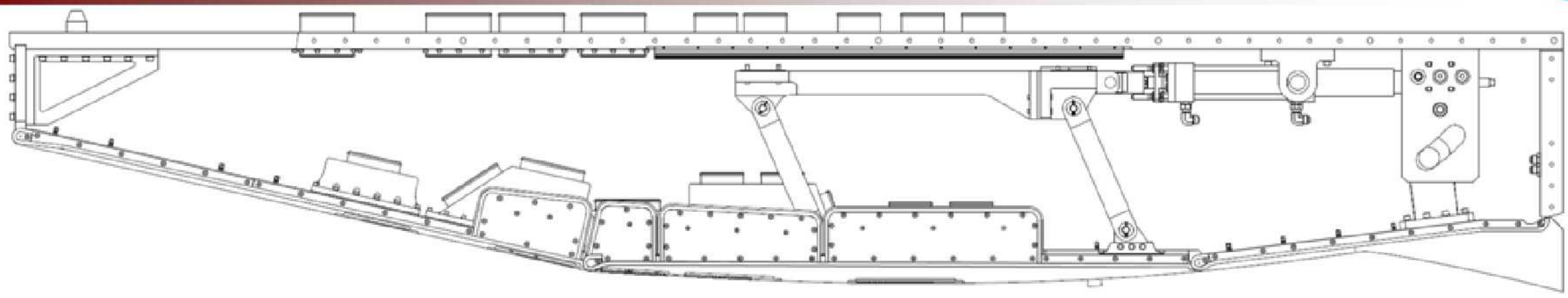
	Static	Rake	Translating Probe	Kulite	Other
High-Speed Inlet	179		2	14	
Low-Speed Inlet	242	120		17	
Low-Speed Throat	39	76			
Cold pipe	8				
Bleed Plenums					26
TOTAL	468	196	2	31	26

Not included in count:

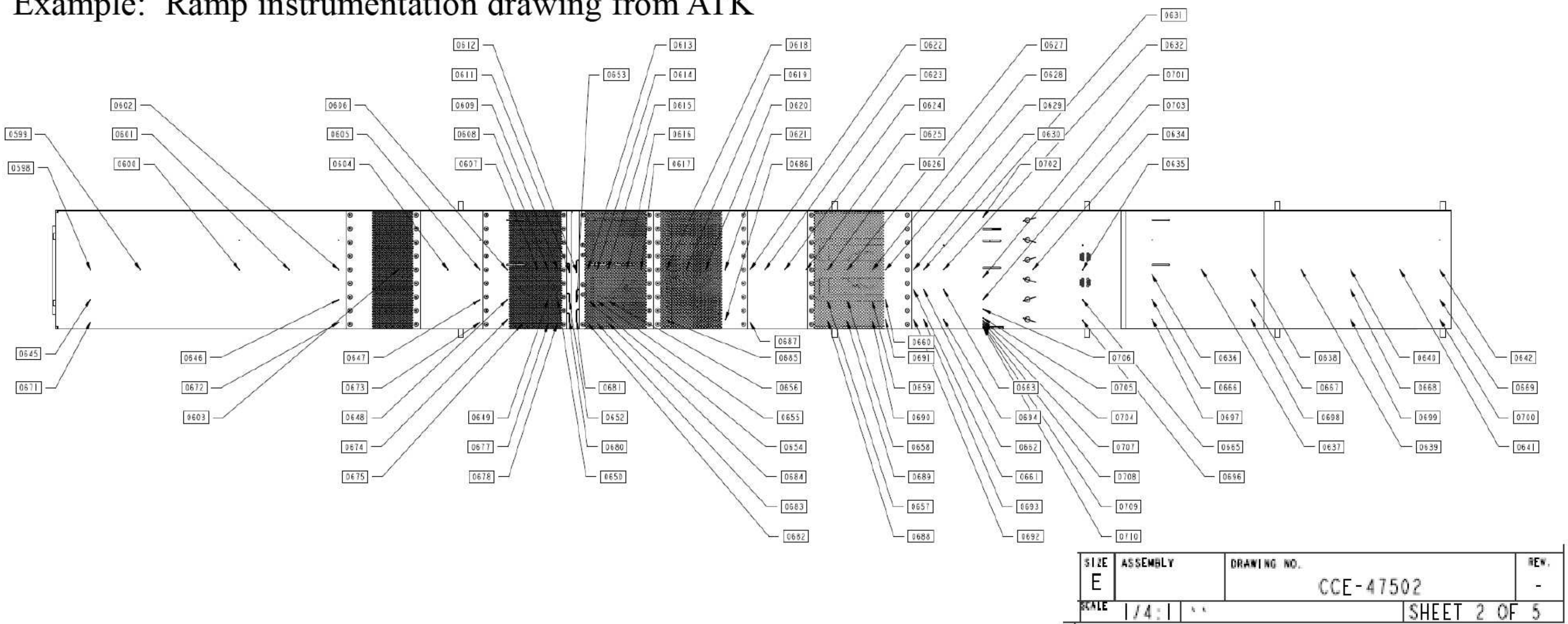
- Expansion plate instrumentation ---- rakes(22)
- High-speed inlet isolator exit instrumentation ---- statics(8?), rakes(25)
- Bleed pipe instrumentation ---- statics(~60), rakes(?)
- Low-speed inlet AIP instrumentation (VIIPAR rake array) ---- statics(8), rakes(72), kulites®(40)

Grand total: statics(544), rakes(191), x-probe(2), kulites®(71), acceler(12), other(26)

CCE Mode-X: inlet instrumentation



Example: Ramp instrumentation drawing from ATK



Instrumentation drawings are underway, computing in development

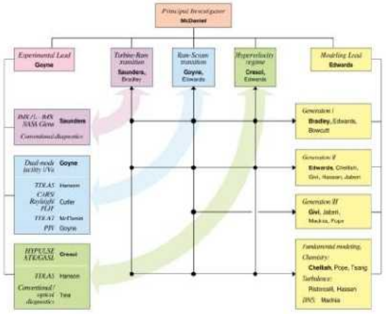
Center Goals

(National Center for Hypersonic Combined Cycle Propulsion)

Focus Area 2: Benchmark data sets for RANS, hybrid LES/RANS, and LES models
- high- and low-frequency wall static and dynamic pressures
- flowfield rakes, mass flow measurements and schlieren.
- focus on *second-generation* hybrid LES/RANS numerical methods

Focus Area 3: Performance improvements and control of mode-transition
- control schemes for the turbine to ramjet transition
- actual turbine engine to be installed in the low speed flowpath

Preliminary schedule:
- year 1: Collaboration of NASA and center teams, Inlet testing
- out years: Controls testing, turbine engine testing



CCE / LIMX = **C**ombine **C**ycle **E**ngine / **L**arge-scale **I**nlet **M**ode Transition

CCE Mode-X October 1st Summary

- A rational plan to address Combine Cycle Engine mode transition has been planned with fabrication underway and testing planned for early 2010.

- The 10x10 SWT provides a unique facility to address large-scale testing for this mode transition research and demonstration.

- Full-scale HiSTED-class turbines such as the modified WI WJ-38 has been incorporated. SLS Tests of Engine/ Nozzle planned late summer at WI. Plans are in place for integrated Mode-X testing with modified WJ-38 in 2011/12.

- The 10x10 SWT has tested large supersonic turbines like the J-85, TF-30 engines. The tunnel's maximum engine size is nominally a J-58, ~50" diameter engine.

- Turbine engine and high-speed propulsion expertise at NASA provides the depth and large facilities (10x10, 8x6 SWTs, 8'HTT and PSL) to address critical need for CCE mode transition research.

NASA Hypersonics project will address key elements of CCE mode transition

BACK-UP CHARTS

- Objective statements
- Air-breathing propulsion modes
- Conceptual Geometry
- 1x1 IMX results (from JANNAF)
- Old test plan charts, (Techland has new ones)
- Mech. Design / Tunnel layouts
- Teaming: to date + NCHCCP / UVa
- Instrumentation conceptual layout
- Project charts (Suder) + issues from April, during Jim Pittman visit
- Recent fabrication issues
- Translating cowl
- Boeing CFD
- Distortion
- Ramp actuation redesign??
- 1x1 IMX High Speed video sequence (external, separate ppt file)

- John’s CFD charts for Bremen
- Other test activities
  - 15x15 isolator
  - 1x1 plans / AFRL
  - bleed experiments
- Isolator performance, Istar experience
- 10x10 control room and staffing

Air-breathing Combined Cycle Propulsion Modes

Vehicle Design

- TSTO
- SSTO

Flight Conditions

- M_{inf}
- Altitude
  - q, Ttot, Po
- Mstart ~2
- Mtrans ~ 4
- Mstage ~ 7
- AoA ~ 4°
- Yaw ~ 0°

Perturbations

Propulsion Flowpath

TBCC
- overunder
- cocooned

RBCC
- single flowpath

Inlet Config.

Low-speed
- mixed/ext. compression
- Mach throat~ 1.3
- var. geom.
- turning
  - Inward
  - Rect.
  - Axi.
- bleed

High-spd
- Mach throat ~1/2 M_{inf}
- var. geom. ??
- turning
  - Inward
  - Rect.
  - Axi.
- isolator/bleed

Perturbations

Engine Aspects

Turbine
- dry
- afterburner
- stall ?
- windmill ?
- fuel type -HC

Ram/Scram
- Fuel stage ?
- var. geom. ?
- Mach ignite ?
- fuel type
- cross-section -circle

Beamed
- . . .

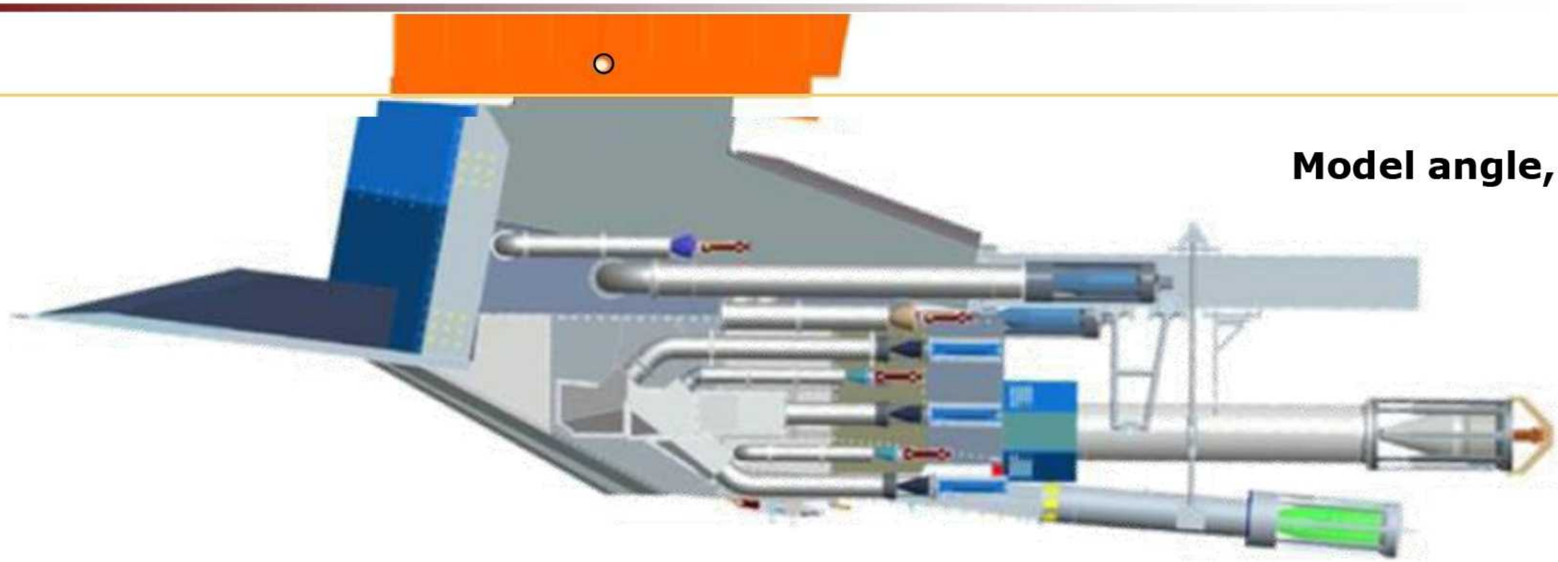
Nozzle Aspects

Low-speed
- var.geom.
- ejection
- ext. burn
- tail rockets

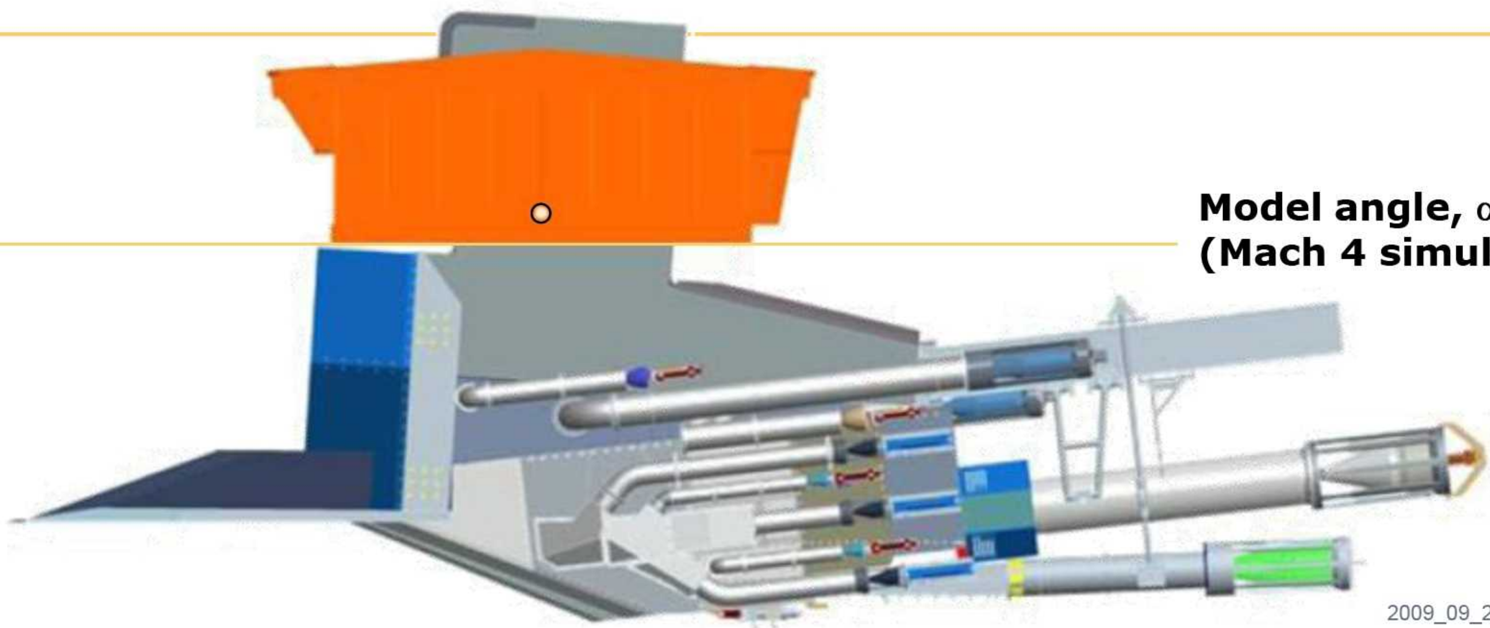
Scram
- fixed ?
- variable geo.

CCE Design is a subset of mode variation

Orientation for Mach 4 simulation in 10x10 SWT



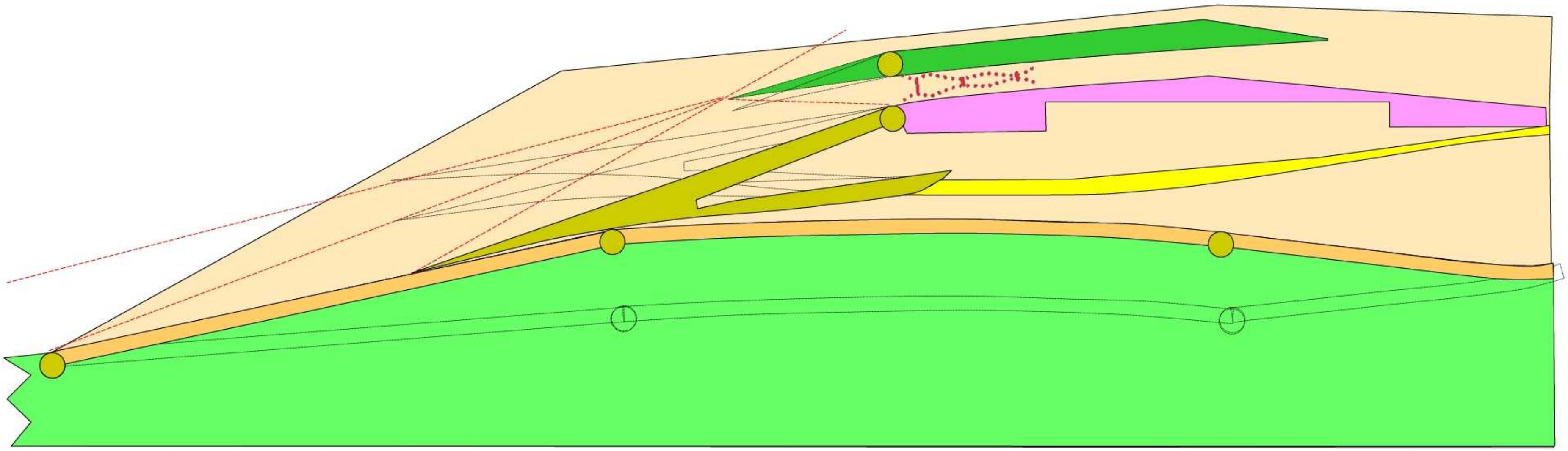
Model angle, α = 0º



Model angle, α = -7º
(Mach 4 simulation)

Mach number / mode transition with shocks

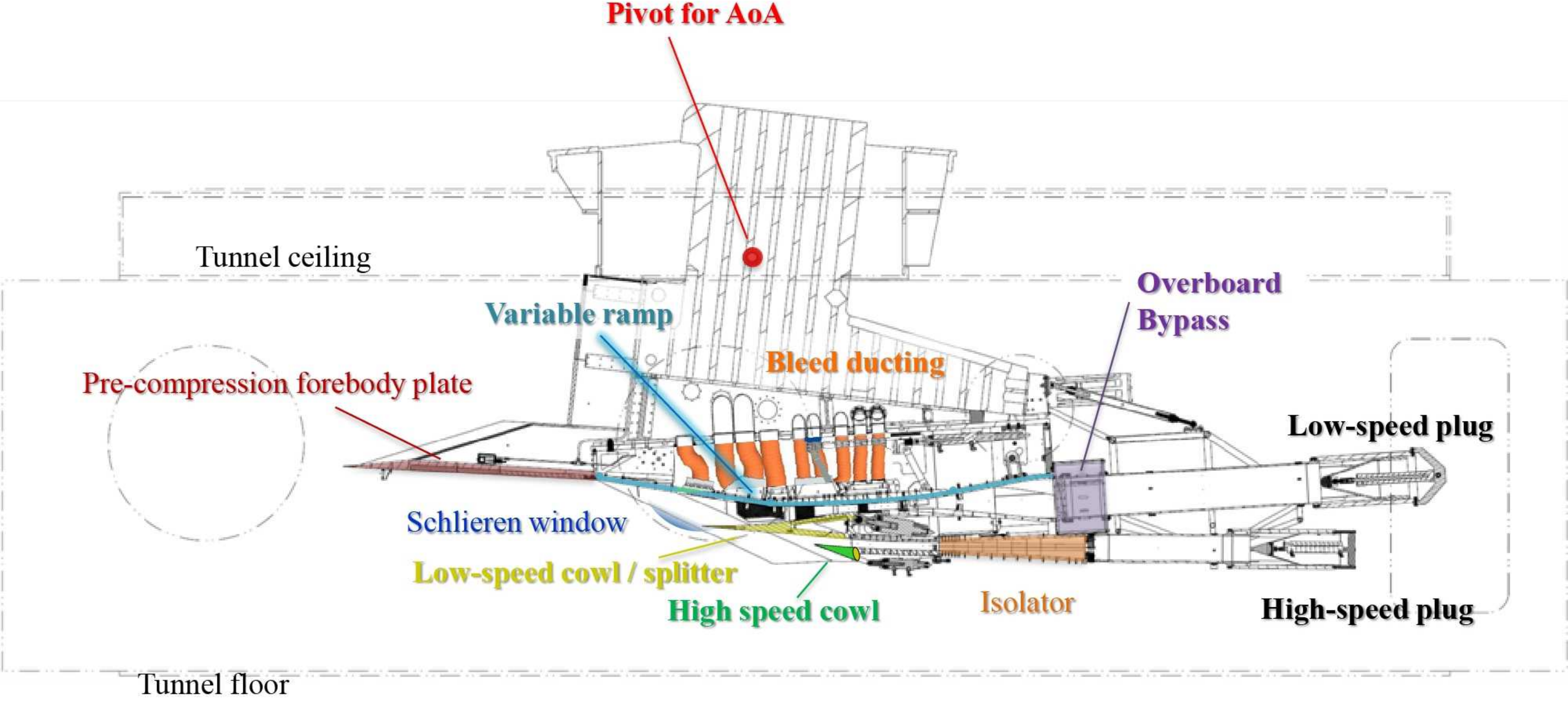
M = 7 low-speed closed.



Mode transition sequences

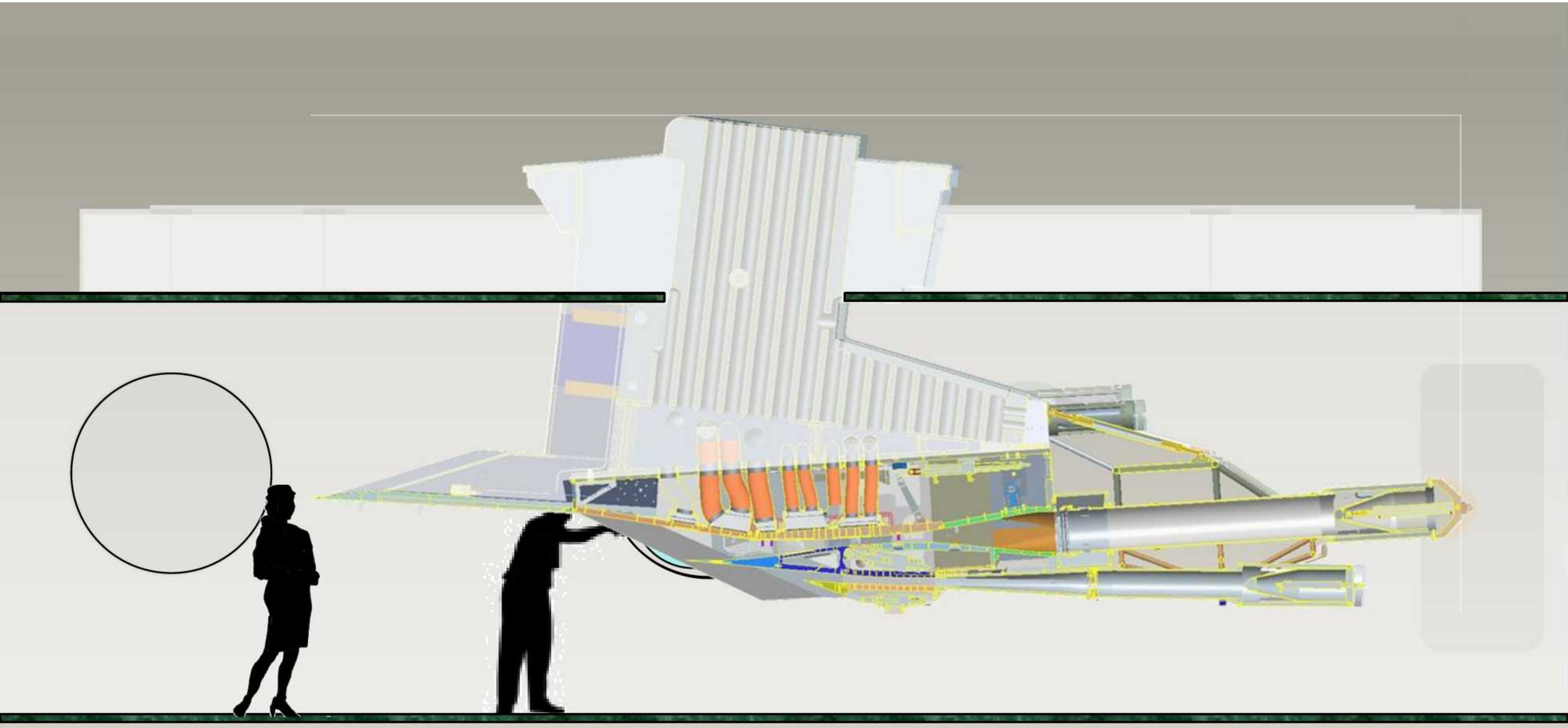
Variable geometry ramp inlet configurations.

CCE-LIMX: Key model elements



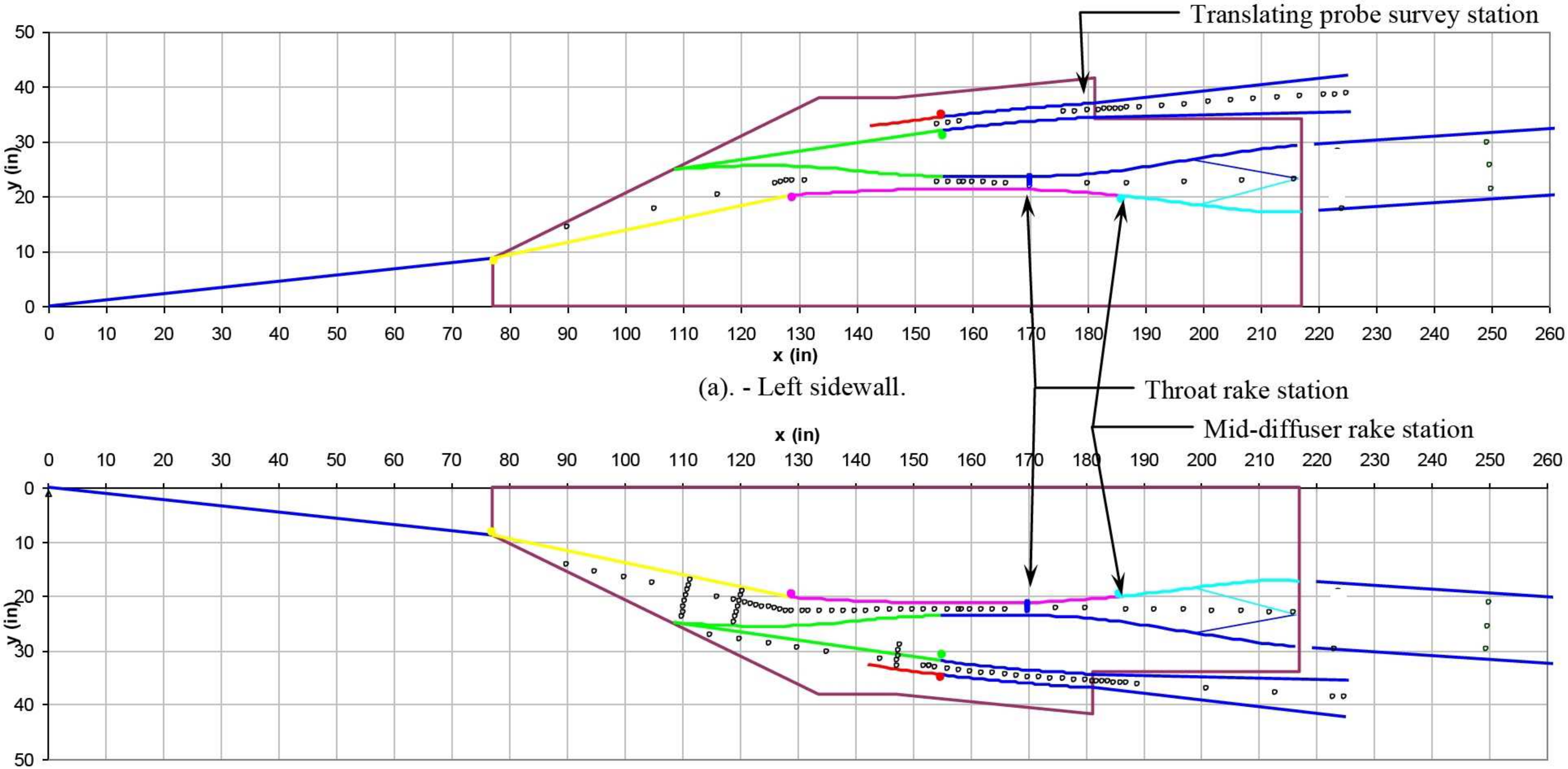
Variable geometry in **Bold**

CCE – Large scale Inlet Mode Transition model



10x10 SWT Installation, original position

TBCC-LIMX: instrumentation

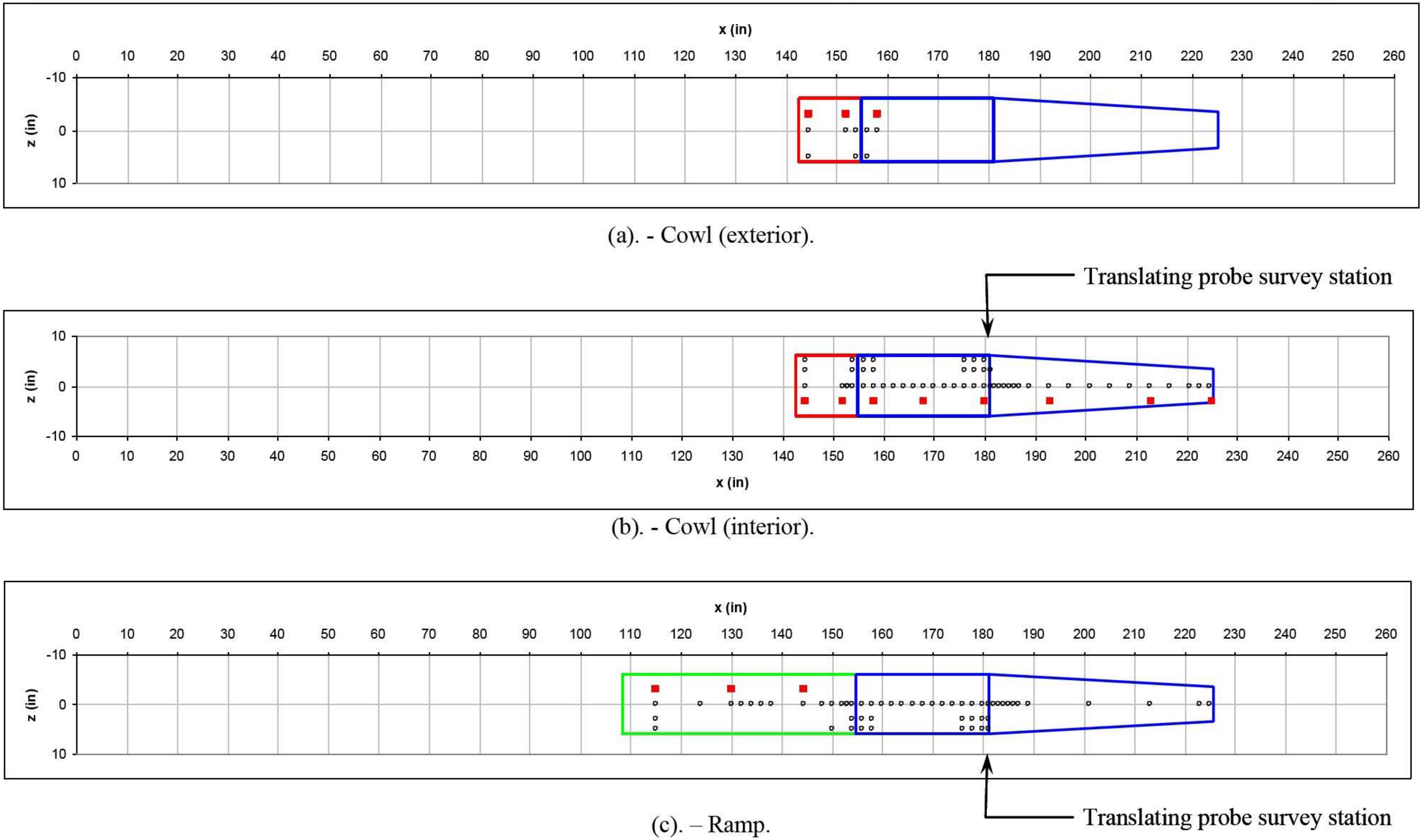


(a). - Left sidewall.

(b). - Right sidewall.

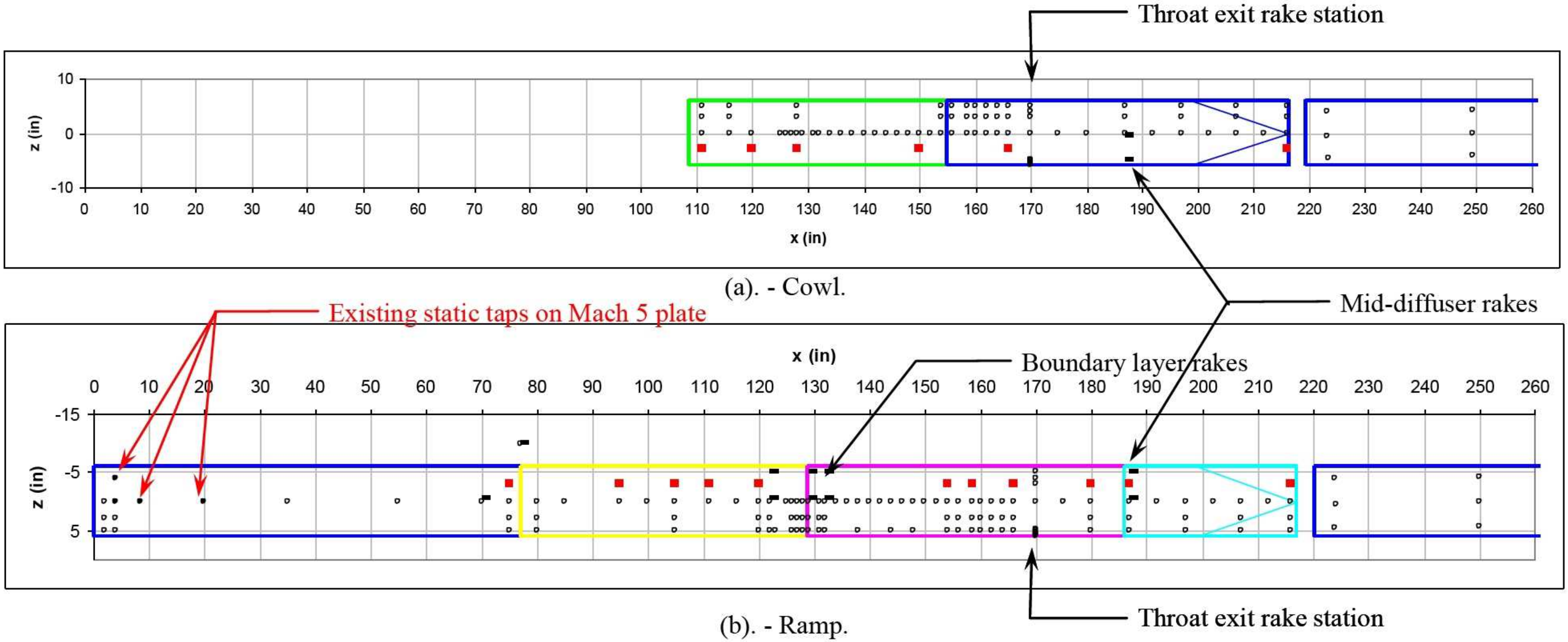
Sidewall surface static pressure instrumentation.

TBCC-LIMX: instrumentation



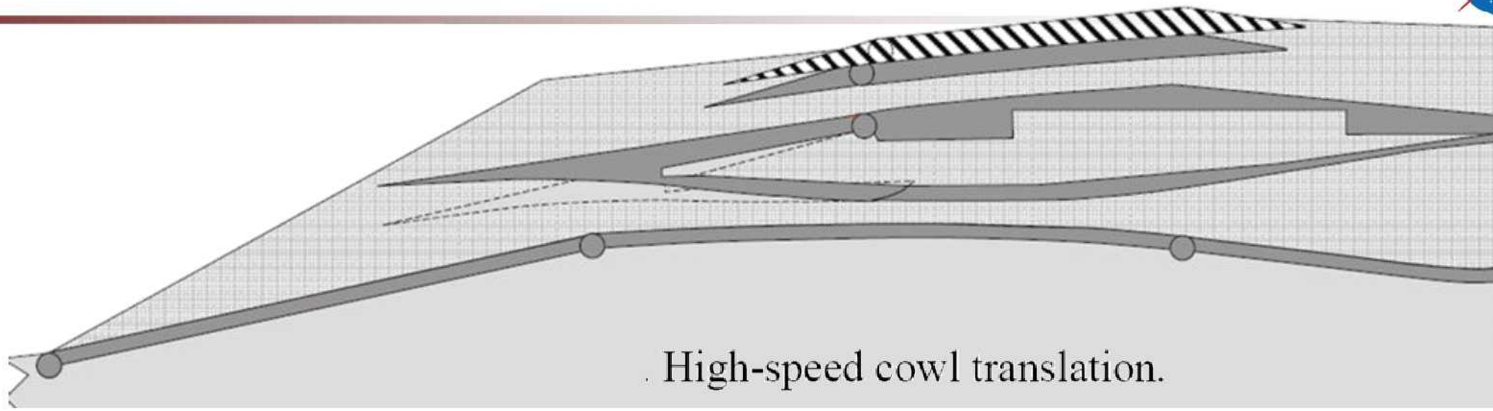
High-speed inlet surface static pressure instrumentation.

TBCC-LIMX: instrumentation

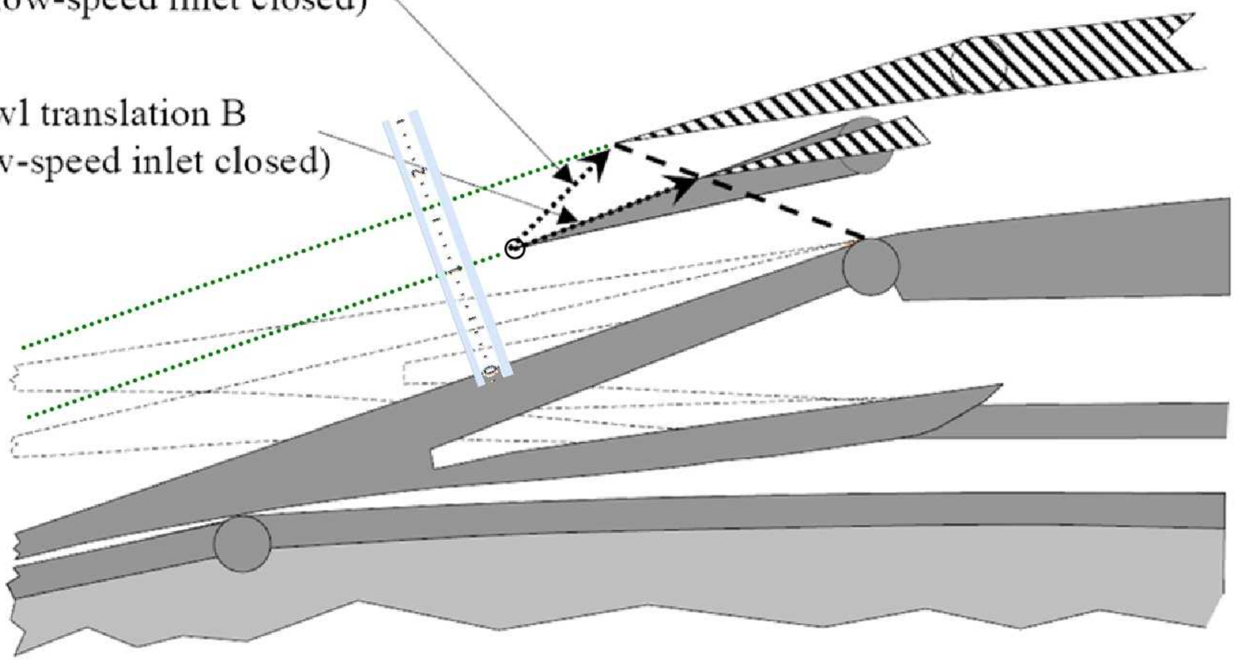


Low-speed inlet surface static pressure instrumentation.

CCE LIMX translating high-speed cowl



. High-speed cowl translation.

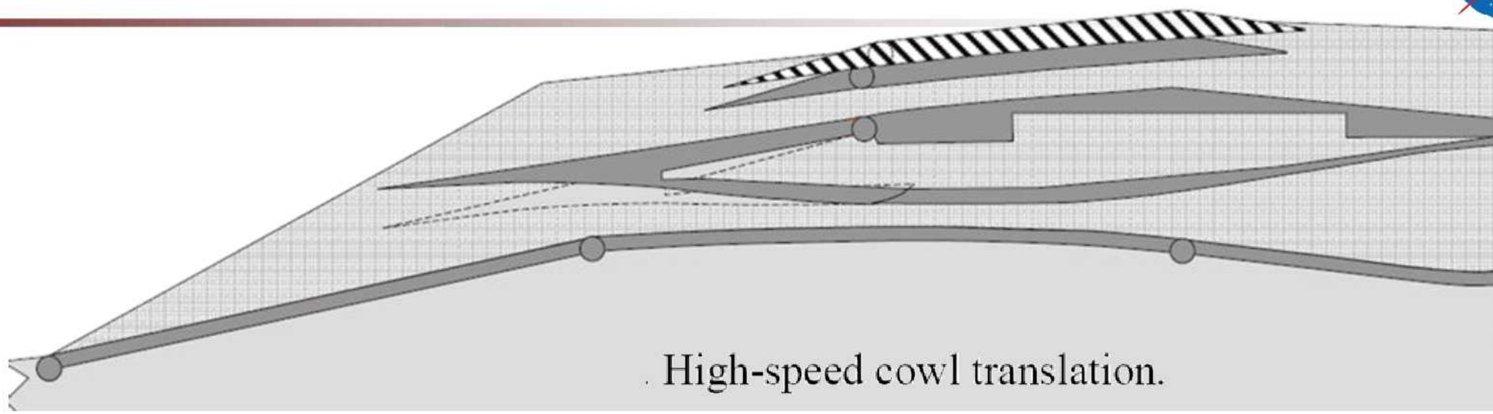


Possible high-speed cowl translation schedules.

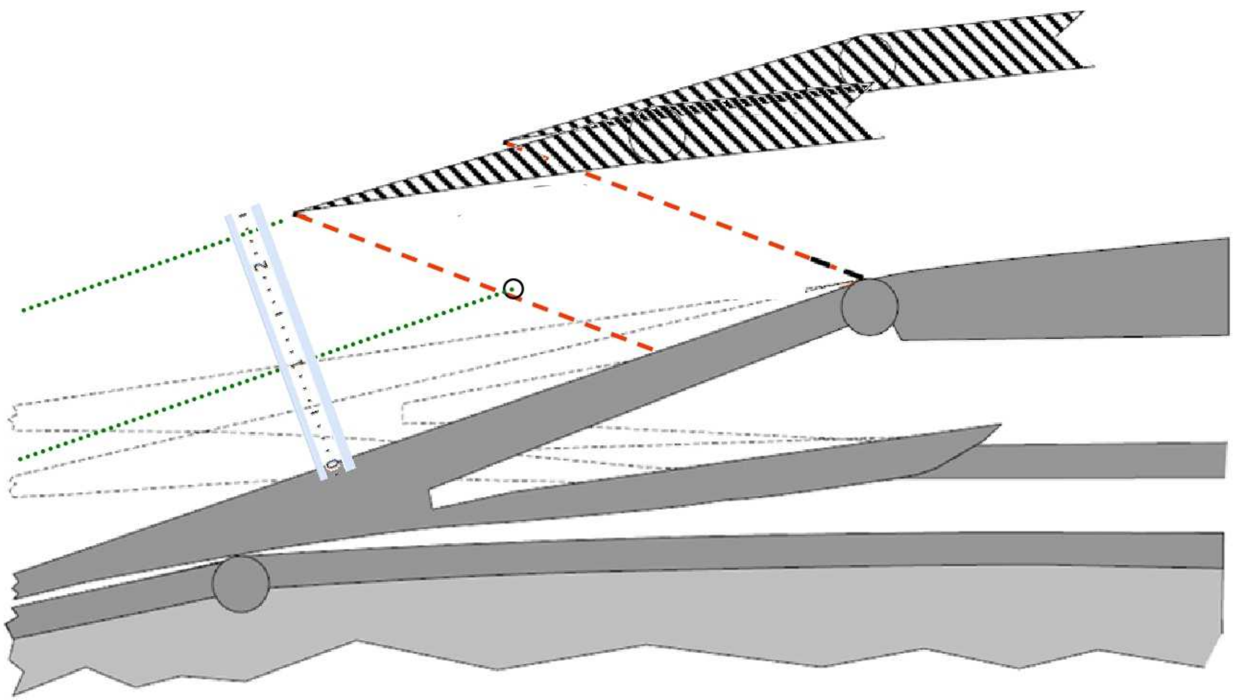
60% increase in
high speed capture
for ‘translation A’

From:
CR-2008-215214

CCE LIMX translating high-speed cowl



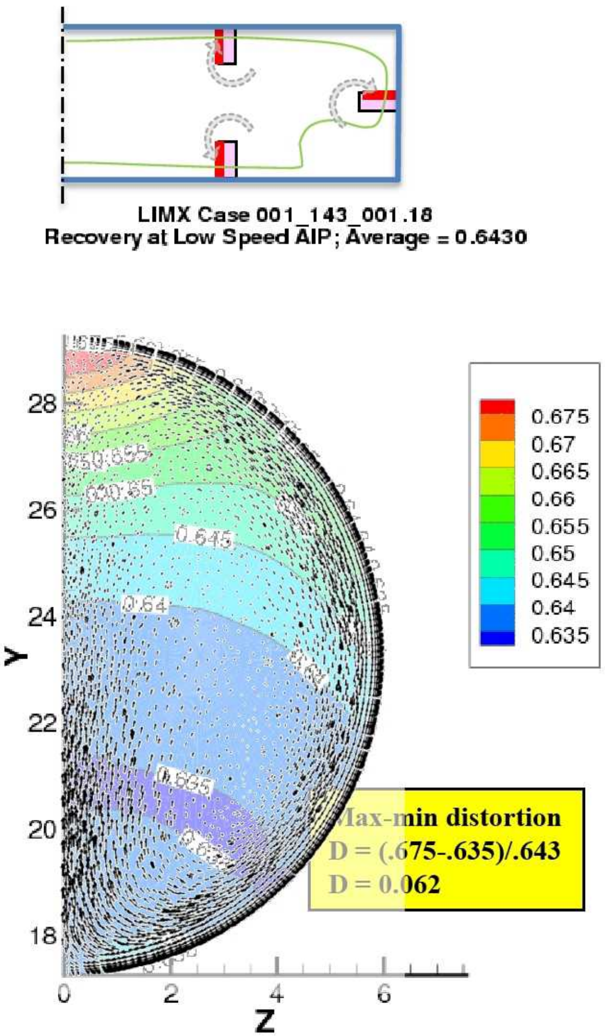
. High-speed cowl translation.



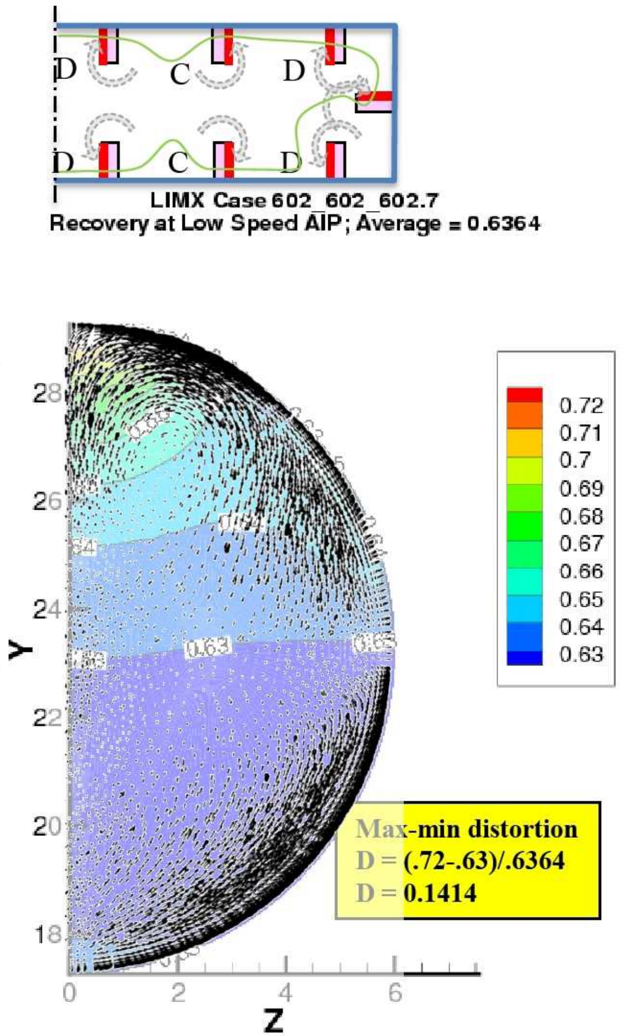
Possible high-speed cowl translation schedules.

125% increase in high speed capture for more aggressive translations

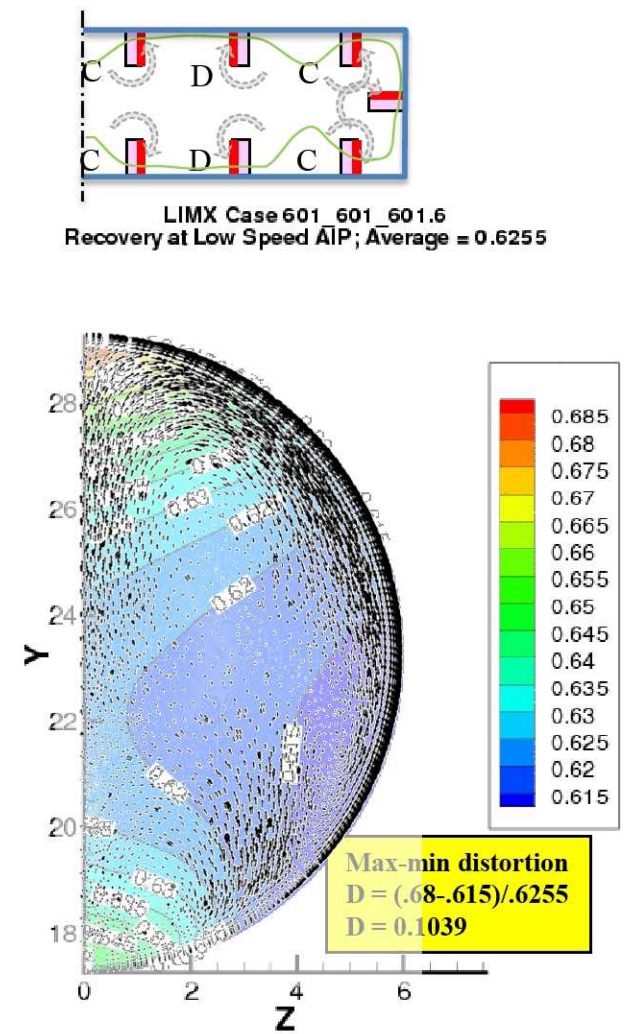
Vortex generator effects, (Boeing CFD)



AIP flow field for Basic VG Configuration

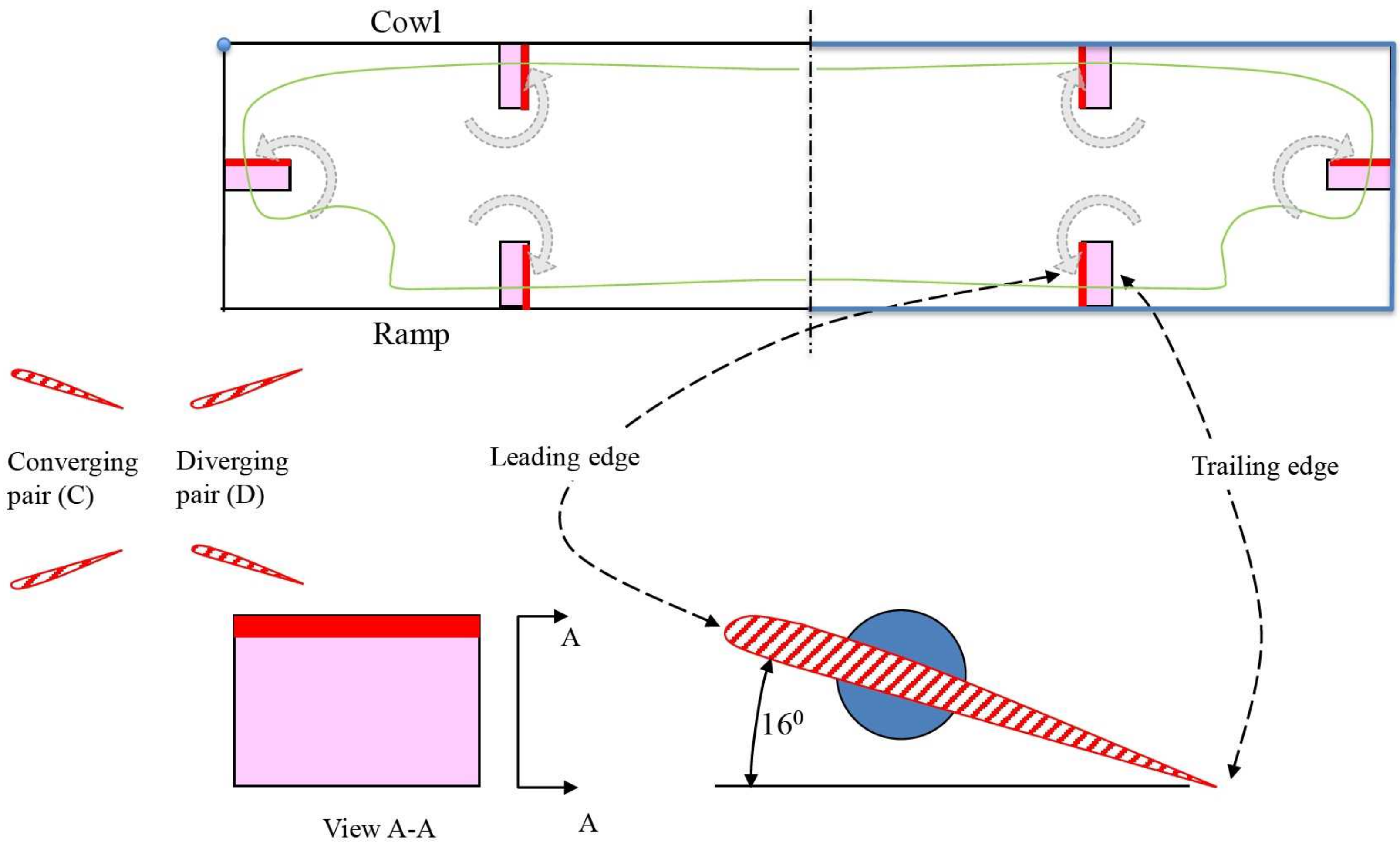


AIP flow field for the Alternate VG Configuration



AIP flow field for Alternate-Opposite VG Configuration

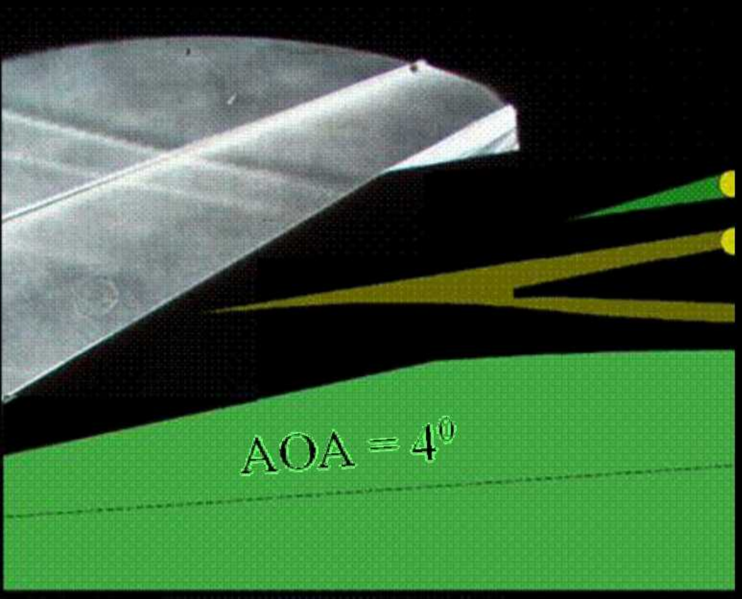
Baseline Configuration

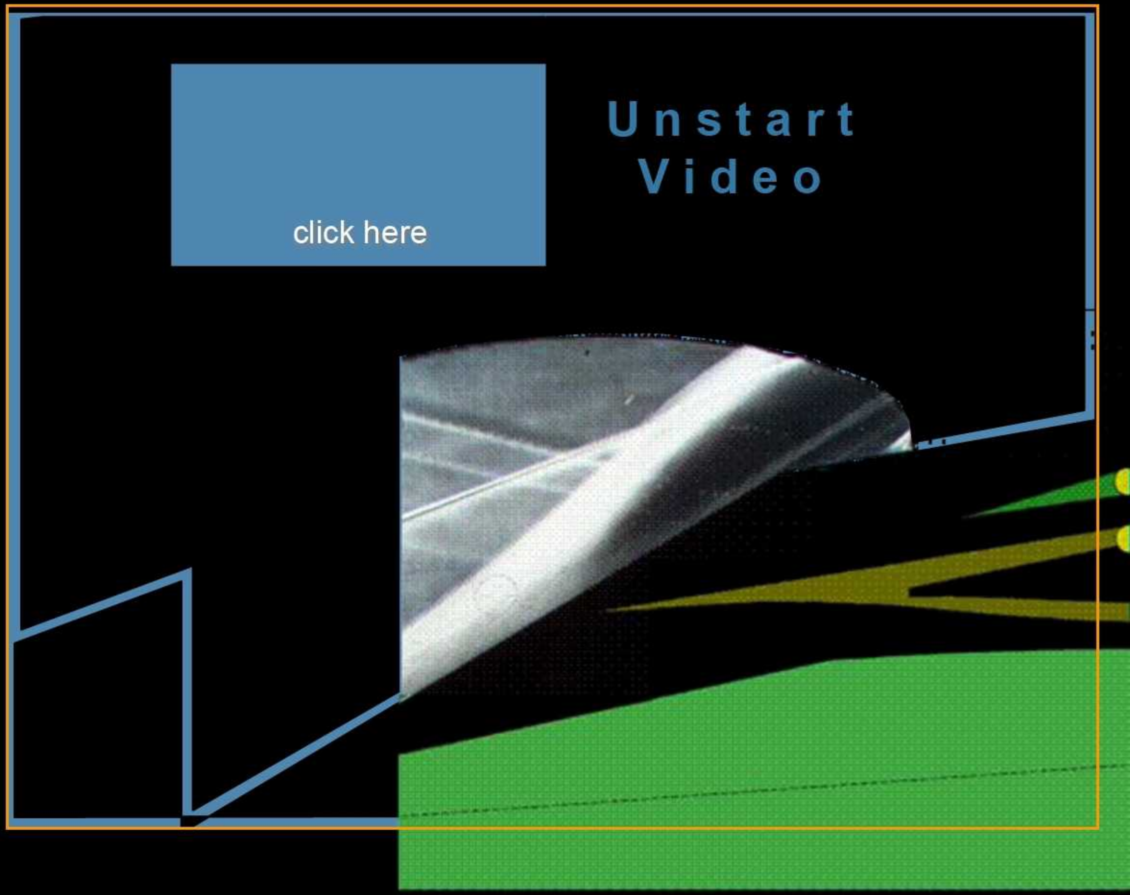


Orientation of vortex generators at station 173.987 (down stream view) Dimensions are presented in the CRD - Figure 27.

Schlieren video showing buzz: IMX at Mach 4

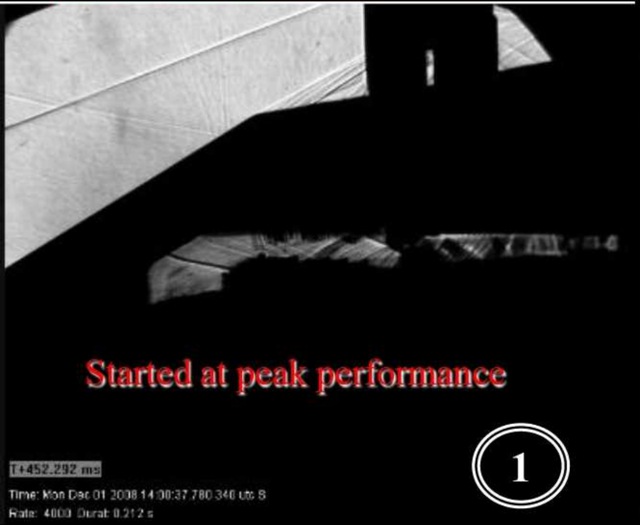
Started





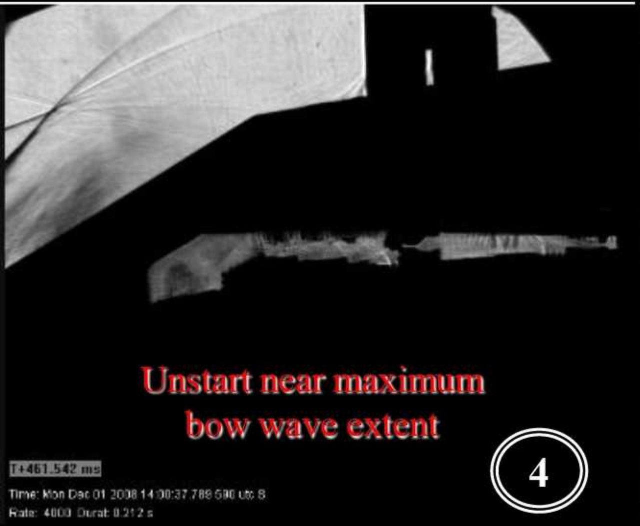
Inlet Unstart dynamics are severe with high internal comp.

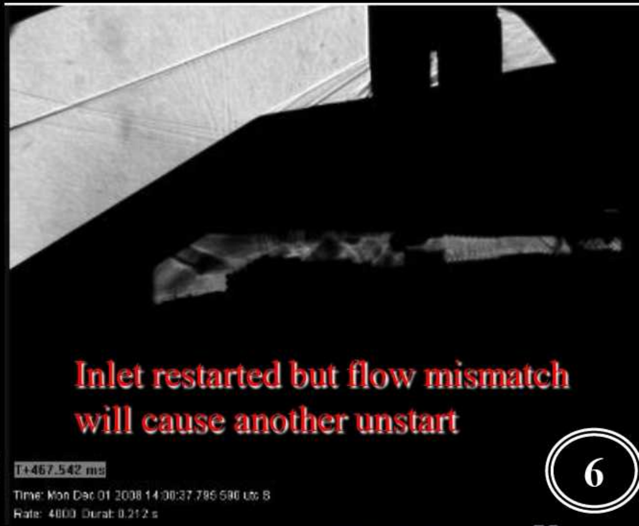
High Speed Schlieren from 1x1 SWT, IMX model



High-Speed Video at Mach 4

Unstart Transient -- 4000 frames/sec





S

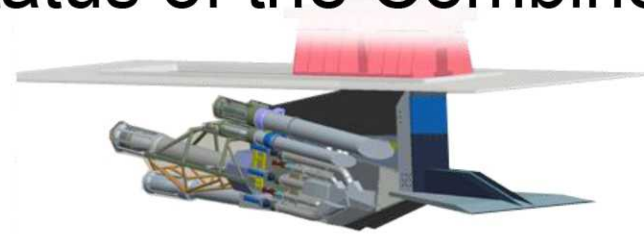
STATUS OF THE COMBINED CYCLE ENGINE RIG

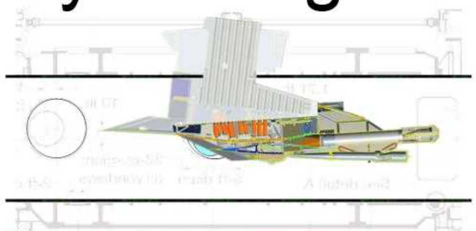
Status for the past year is provided of the turbine-based Combined-Cycle Engine (CCE) Rig for the hypersonic project. As part of the first stage propulsion of a two-stage-to-orbit vehicle concept, this engine rig is designed with a common inlet that supplies flow to a turbine engine and a dual-mode ramjet / scramjet engine in an over/under configuration. At Mach 4 the inlet has variable geometry to switch the airflow from the turbine to the ramjet / scramjet engine. This process is known as inlet mode-transition. In addition to investigating inlet aspects of mode transition, the rig will allow testing of turbine and scramjet systems later in the test series. Fully closing the splitter cowl "cocoons" the turbine engine and increases airflow to the scramjet duct. The CCE Rig will be a testbed to investigate integrated propulsion system and controls technology objectives. Four phases of testing are planned to 1) characterize the dual inlet database, 2) collect inlet dynamics using system identification techniques, 3) implement an inlet control to demonstrate mode-transition scenarios and 4) demonstrate integrated inlet/turbine engine operation through mode-transition. Status of the test planning and preparation activities is summarized with background on the inlet design and small-scale testing, analytical CFD predictions and some details of the large-scale hardware. The final stages of fabrication are underway.

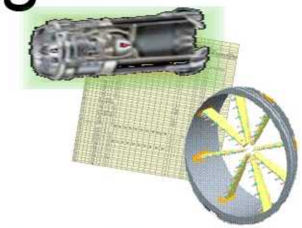
National Aeronautics and Space Administration

Hypersonics Project

Status of the Combined Cycle Engine Rig





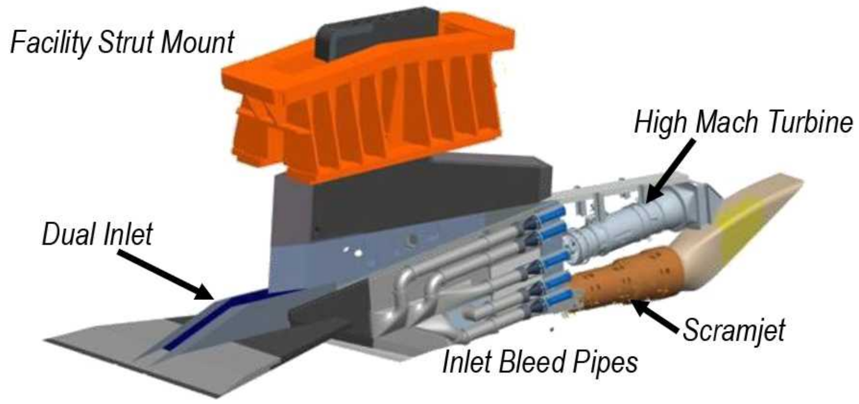


Dave Saunders
John Slater
Vance Dippold

2009 Annual Meeting
September 29-October 1, 2009

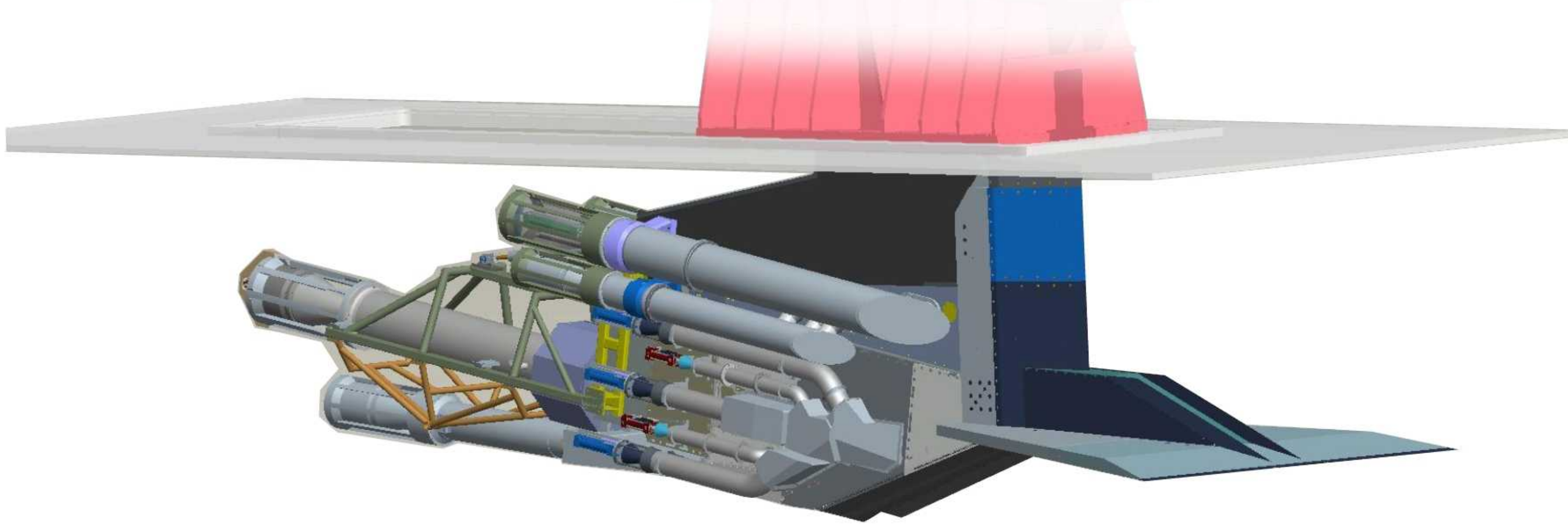
Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, how, when, who, why?
- Background: Inlet Design / small-scale test
- CFD predictions
- Test Planning
- Instrumentation
- Summary



What is CCE mode transition?

Combined Cycle Engine mode transition is a research and demonstration project to show high propulsion performance can be maintained while transitioning between a turbine engine and a dual mode ram/scramjet

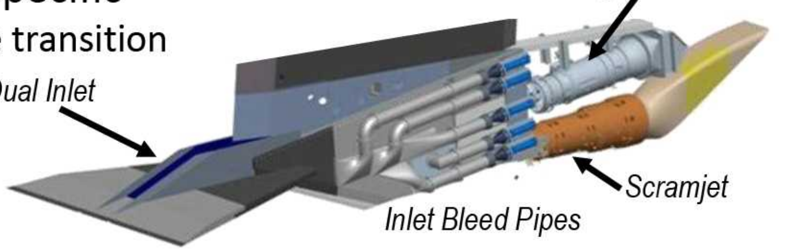


- Inlet Objective: Provide a controllable dual-flowpath inlet testbed suitable for mode transition research. Includes an inlet performance and operability database.
- Controls Objective: Characterize dynamics and develop a smooth mode transition control through one or more scenarios that maintain propulsion performance.
- Engine Objective: Demonstrate transition with operational engines, (turbine engine is funded).

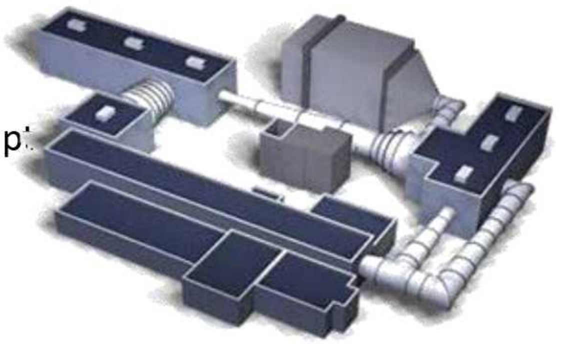
How will CCE mode transition be done?

- **CCE Mode transition is a time sequence between complex propulsion components. Elements are tied together with controls and large-scale testing in a supersonic wind tunnel.**

- **Propulsion Elements and components**
  - Target Design: M7 TSTO booster stage – non-fuel specific
    - Near term focus on inlet and control through mode transition
    - Mid term: turbine engine
    - Far term: scramjet (currently unfunded)
  - Inlet Designed with 2D tools
    - TechLand M5 SBIR study
    - Interaction with NASA for M7 design, M4 mode transition speeds
    - Small-scale inlet testing
  - Wide range, High Mach turbine integration
    - CCE turbine modified by Williams (WJ-38-15 heritage)
  - Scramjet combustor
    - Original design was rectangular for wide hypersonic Mach range
    - Modified for compatibility with ATK round combustor (reduced cap
  - Nozzle
    - Conceptually compatible with dual flow
    - Focused on turbine exit
    - Spiritech design

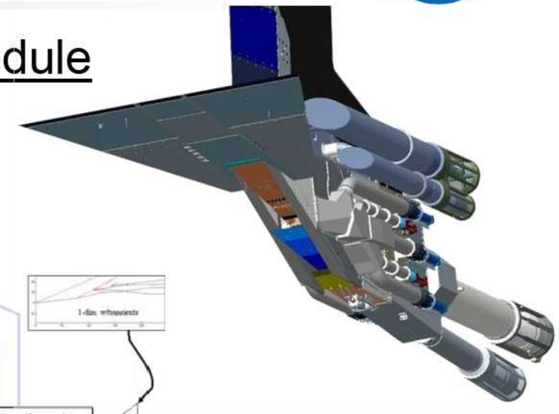


10'x10' Supersonic Wind Tunnel



Mode transition requires large-scale testing, complex components and controls

When will CCE mode transition be done?



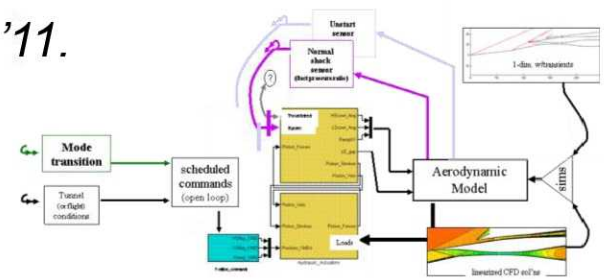
Four+ phases – *three year test program* – cost dictated schedule

(1) Inlet Characterization – *fiscal year '10.*

Controls research – *fiscal year '10 / '11.*

(2) System Identification (SysID)

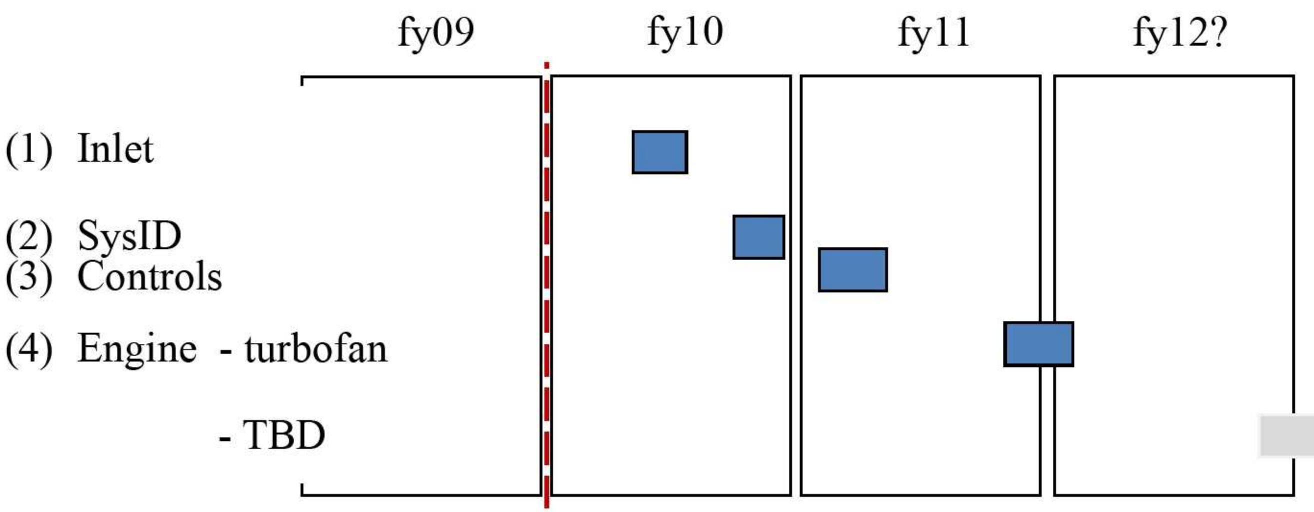
(3) Control Implementation



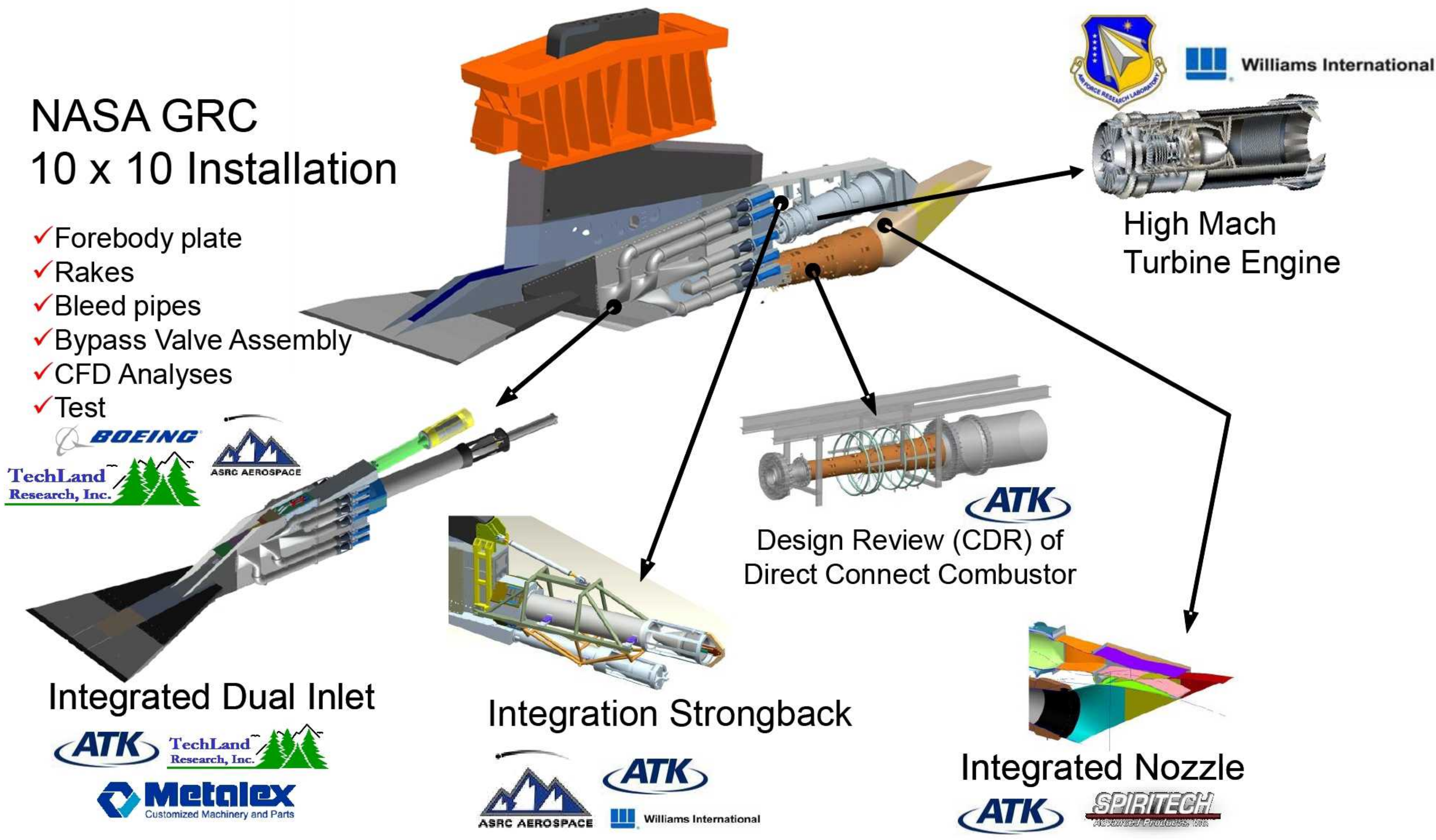
(4) Engine Integration

Turbofan – *fiscal year '11 / '12.*

Scramjet integration – *TBD*



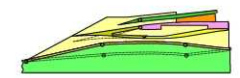
Who: CCE Mode Transition Team



Data reduction will be supported by NASA, NCCCP, and Techland

Why is Large scale testing needed?

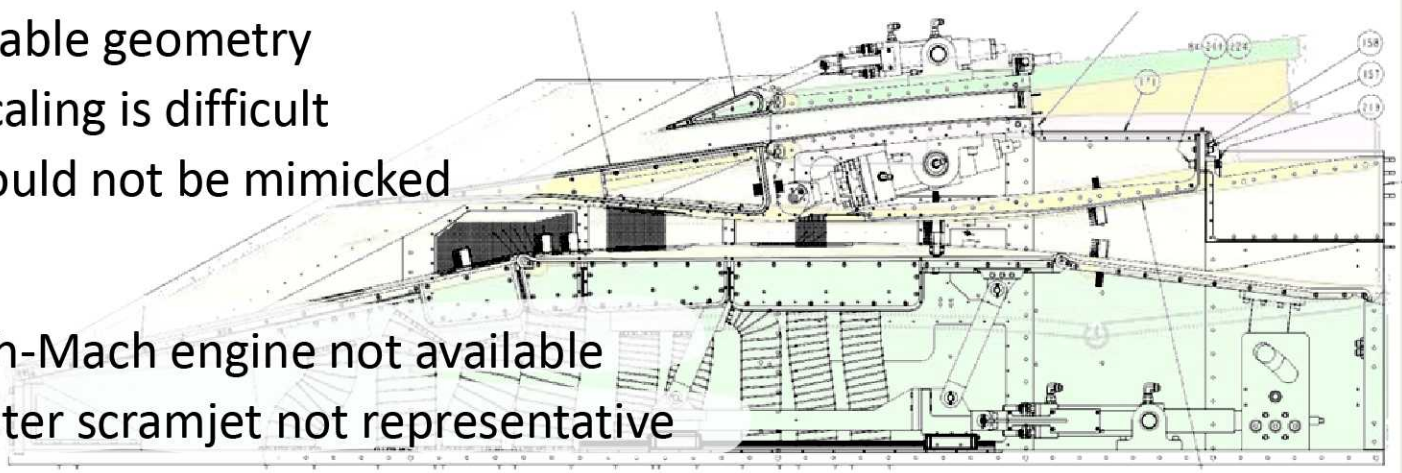
- **Inlet: 1x1 SWT 'small-scale' [~1/7th] screening tests are not high quality for performance**
  - Full mechanical geometry not possible
  - Fixed geometry ramps
  - Actuation through sidewalls causes flow leakage
  - Instrumentation limited, (i.e. 1.82" versus 12" Engine diameter)



small-scale

- **Controls: not possible in small-scale**
  - limited dynamic data
  - lack of variable geometry
  - dynamic scaling is difficult
  - volumes could not be mimicked
- **Engine:**
  - 1.821" High-Mach engine not available
  - 1.2" diameter scramjet not representative

large-scale

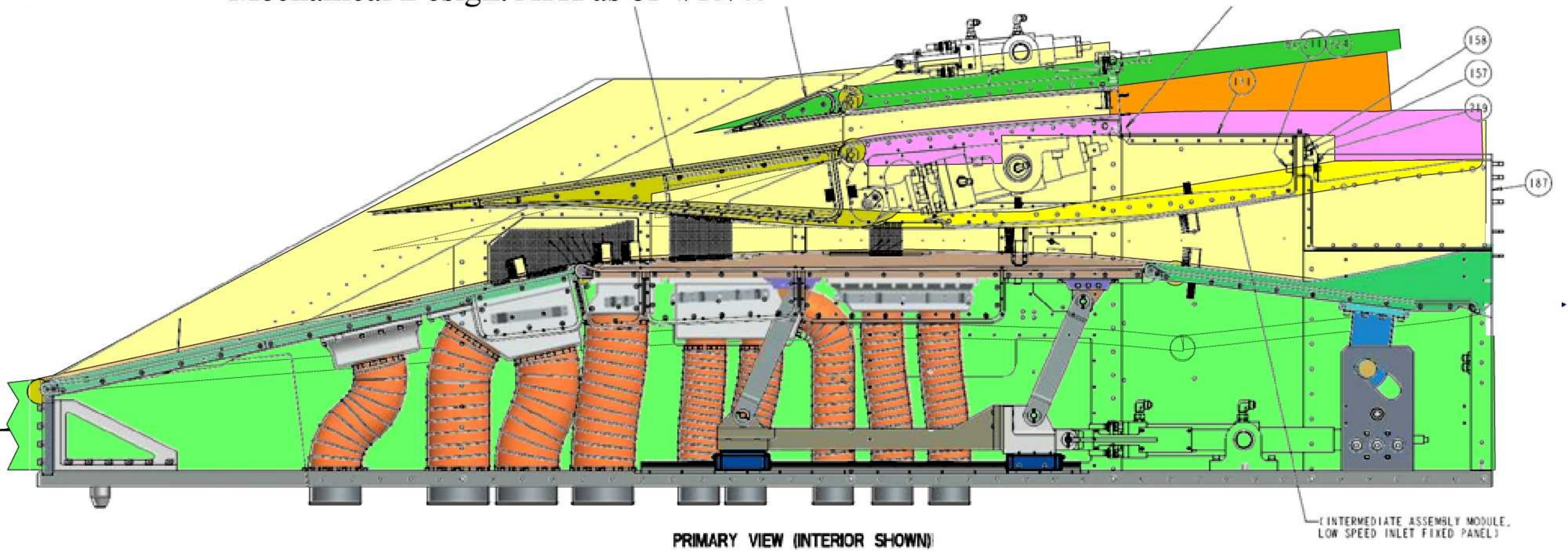


Without all elements, mode transition becomes deficient

Why is Large scale testing needed?

Complexity:

- Conceptual / aero. design from Nov. 2006 -- ref. NASA CR-2008-215215, (Techland Research).
- Mechanical Design: ATK as of 4/13/09



- Variable geometry:
    - Rotating low-speed cowl for mode transition
    - Variable Ramp for Mach Range matching
    - Rotating high-speed cowl for Mach range matching
    - Ten bleed compartments, individually metered
    - Angle of attack, coldpipe/plug metering
- Configurations: vortex generators, bleed patterns, sidewalls, controls/engine integration

Outline: CCE ModeX Aero. Research / Test Planning

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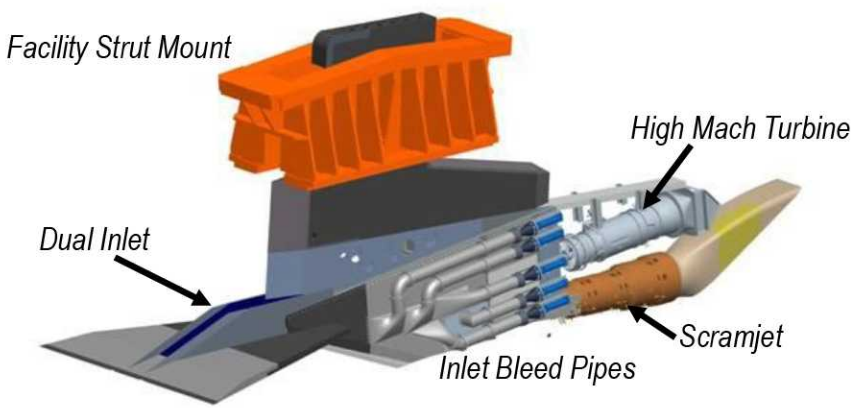
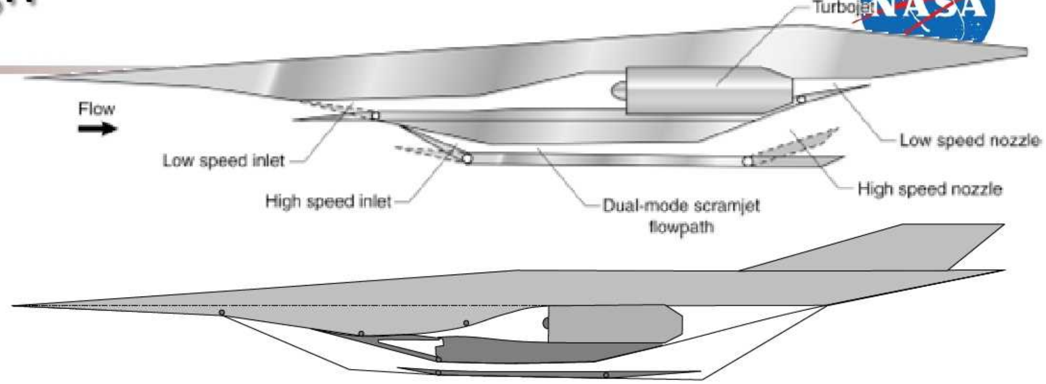
- Inlet Design / small-scale test
- CFD predictions
- Test Planning
- Instrumentation
- Summary



Background: TBCC Inlet Design



- High-speed: Mach 5 over/under
  - (ref. NASA CR-2004-213122)
  - (ref. Albertson/Emami/Trexler)

- Low-speed: supersonics / mixed comp. / bleed / visc.effect
  - Programs: YF-12 / XB-70 / NASP / SST>HSCT

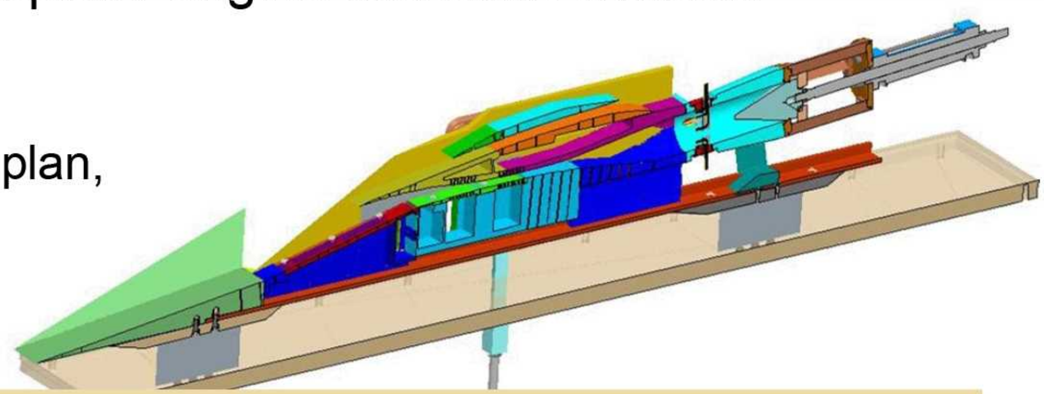
- Integration: vehicle, turbofan, high-speed flowpath

- Mach 7 Hydrocarbon fueled Scramjet with Mach 4 transition from Turbine

- Historical recoveries / Flow splits / engine demand / mission

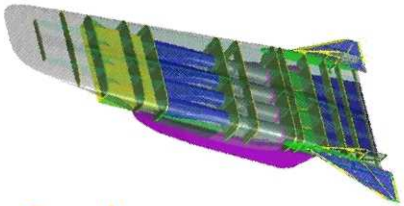
- Impact of CFD:
  - Visualize, Instrument, Test plan,
  - Design, Controls

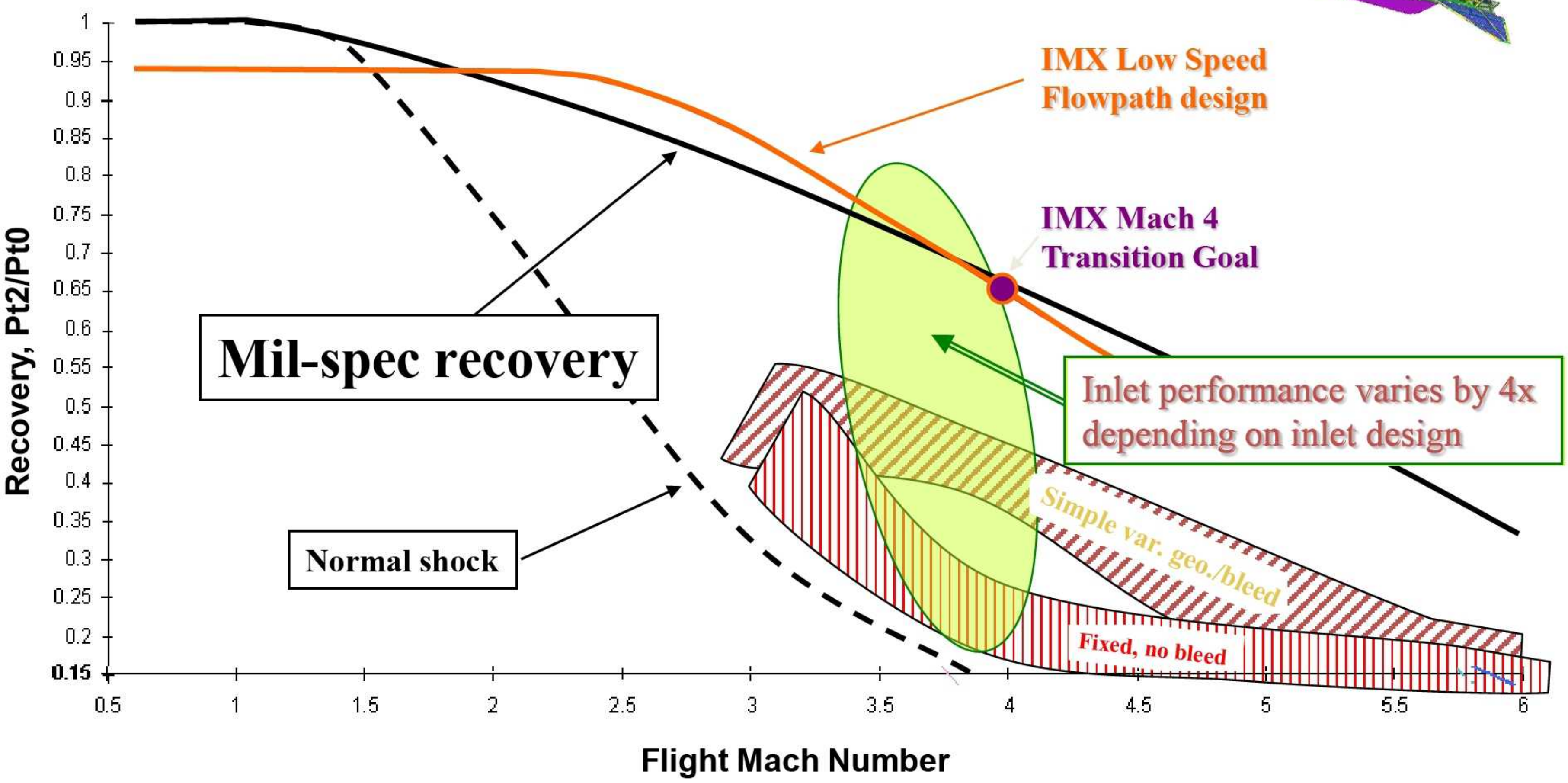
- Small – scale IMX tests



Inlet design driven by TBCC studies, CFD tools, and physical constraints

Background: Inlet performance

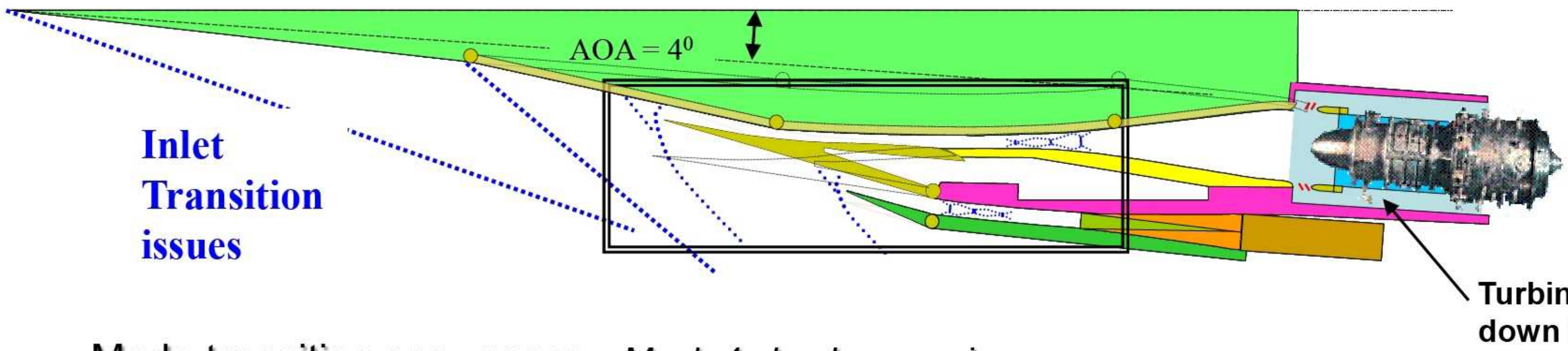




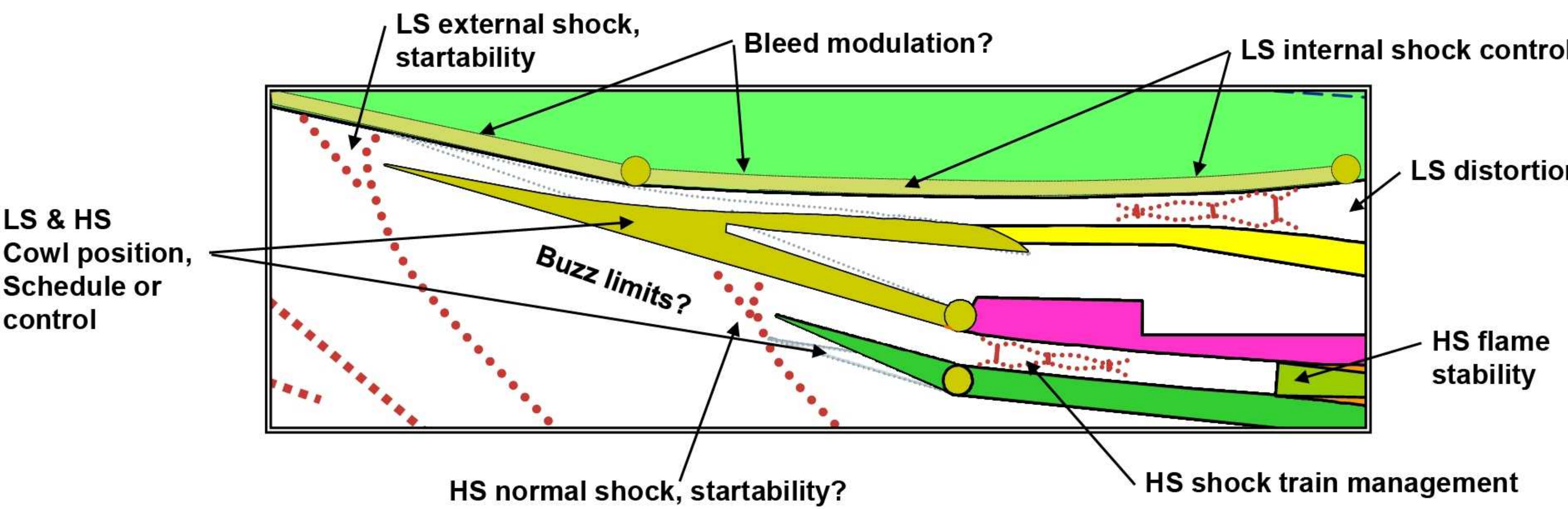
Mil-spec recovery is high performance and requires inlet complexity

Inlet design: requirements for Mode Transition & Wide Mach range

Inlet design driven to complexity: Variable ramp, rotating cowls (2), and bleed compartments (9)



Mode transition sequences: *Mach 4 shock scenarios*

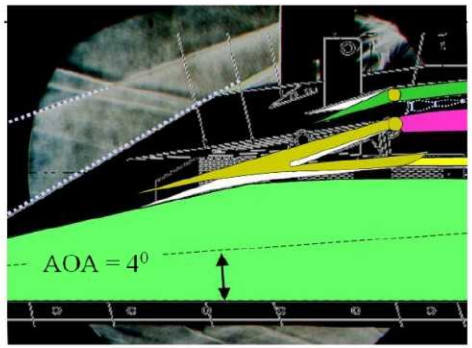


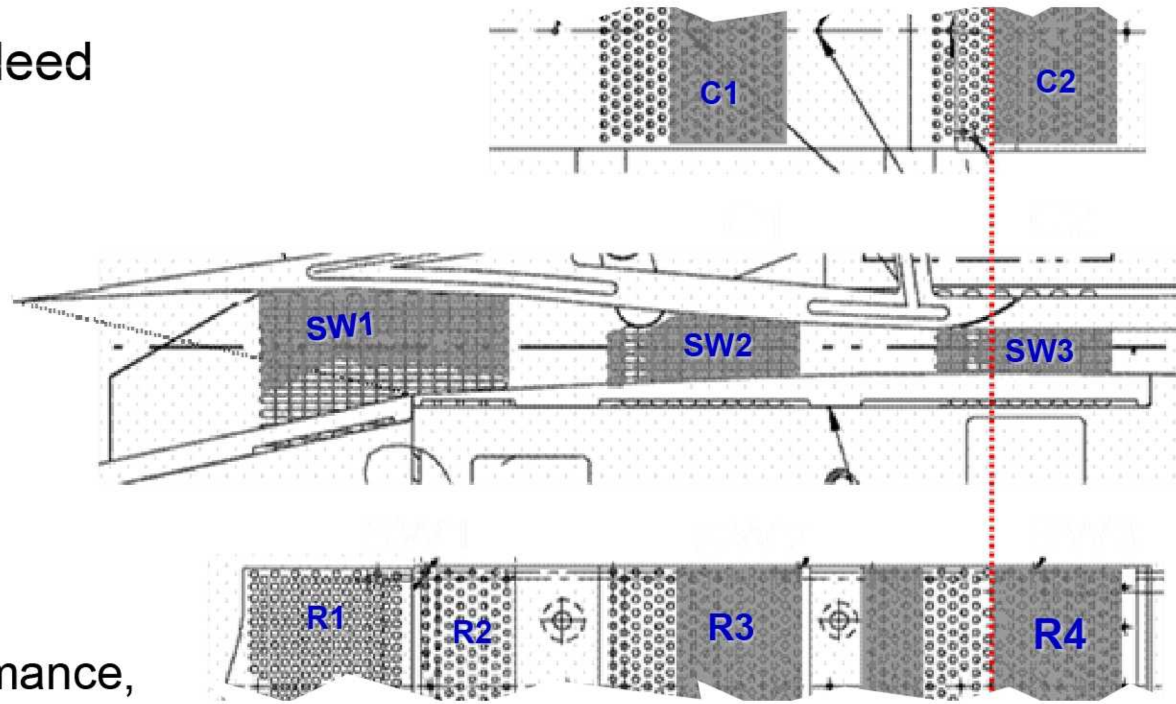
Mode transition design at Mach 4 has complex interactions

1x1 SWT screening results, 69 runs in two phases

- Results discussed in JANNAF report,
  "Inlet Mode Transition Screening Test for a TBCC propulsion system", Boston, 2008

- Configurations / bleed





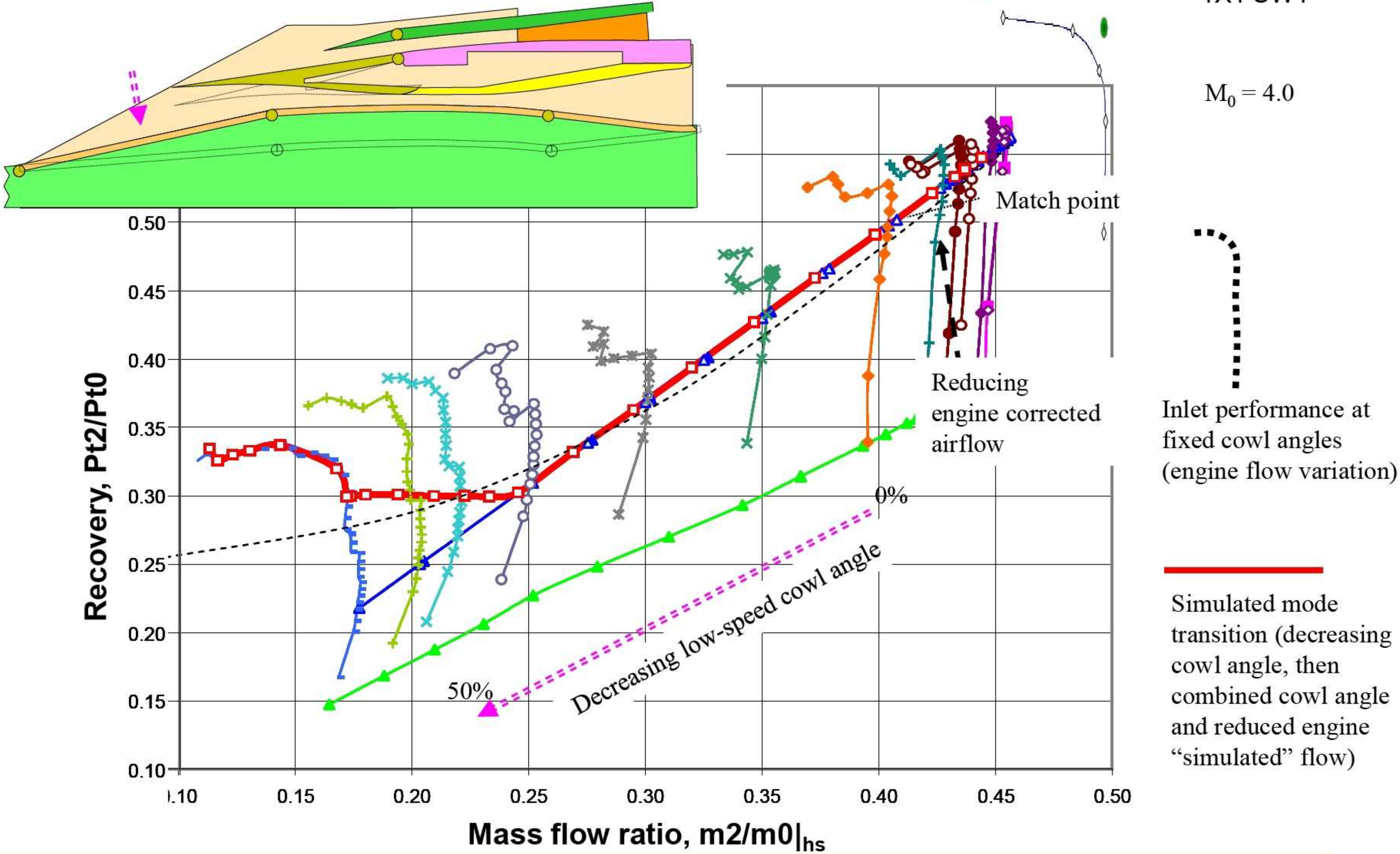
- M4 results:
  good performance,
  popping behavior,
  distortion,
  Mode-transition (mode-x)

- Off-design results: recovery

1x1 experiment completed, inlet design has high performance for mode-x

1x1 SWT screening results: mode-x scenario

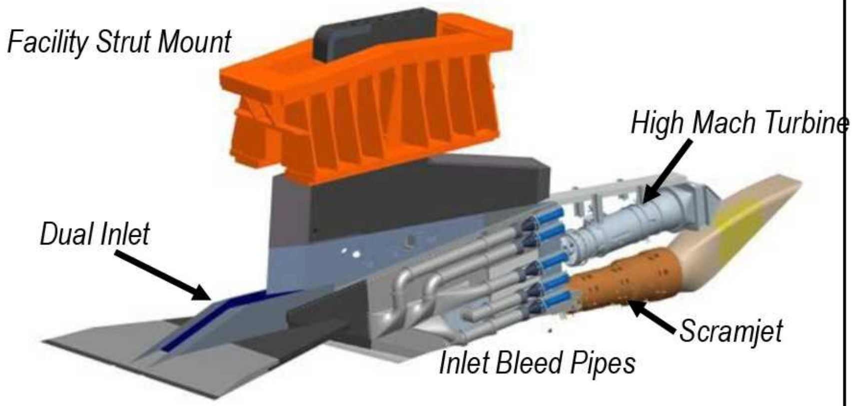
Mach 4 performance & Inlet Mode Transition



Mach 4 performance is near design goal: mode transition is smooth

Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, how, when, who, why?
- Inlet Design / small-scale test
- CFD predictions
- Test Planning
- Instrumentation
- Summary



Overview of CFD Effort from last year's FAP meeting

Objectives

– Provide analysis support of ground testing of the TBCC Inlet Mode Transition (IMX) concept.
– Enhance the understanding of the aerodynamics of inlet mode transition.
– Continue development of CFD tools for high-speed inlet analysis.

IMX-Small-Scale 1x1 SWT CFD Simulations

– Provided estimates of performance, flowfield visualization, and porous bleed characteristics prior and during the 1x1 SWT testing in 2007 (Lee, Slater, and Dippold).
➢ **Post-test analysis of 1x1 SWT data (Run 35) to illustrate the flowfield and validate Wind-US CFD methods (Slater).**
– Post-test analysis of 1x1SWT data (Run 35) to validate BCFD (Boeing).

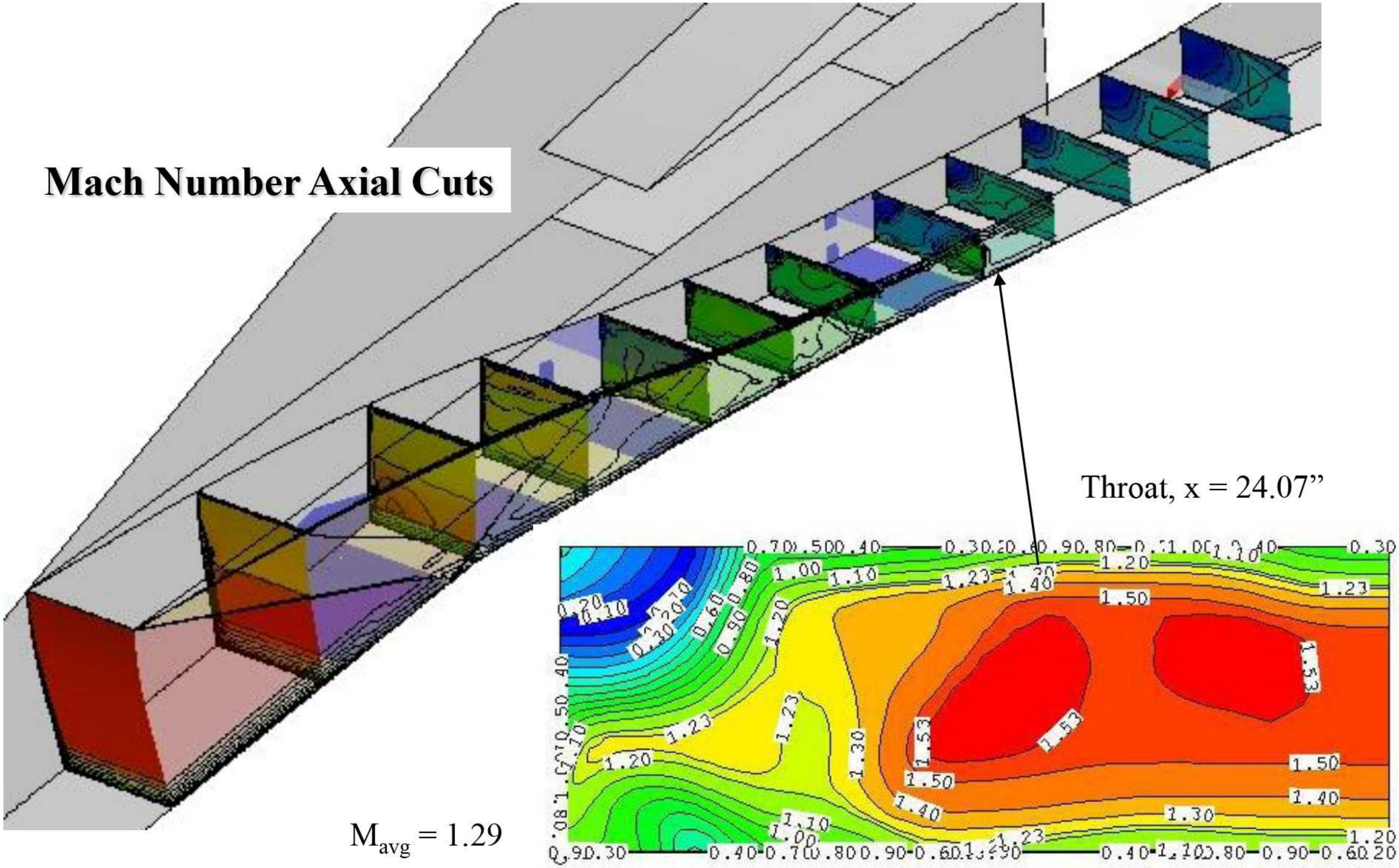
IMX-Large-Scale 10x10 SWT CFD Simulations

– Pre-test analysis of portions of the test matrix to provide visualization of the flowfield, estimations of performance, and effectiveness of porous bleed (Boeing).
➢ **Pre-test analysis of the high-speed flowpath and isolator performance (Dippold).**
– Estimation of flowfield sensitivities with respect to variations in low-speed ramp angle and back-pressure for development of inlet controls (Slater, Boeing).

CFD studies highlighted in bold are those discussed at last FAP meeting…

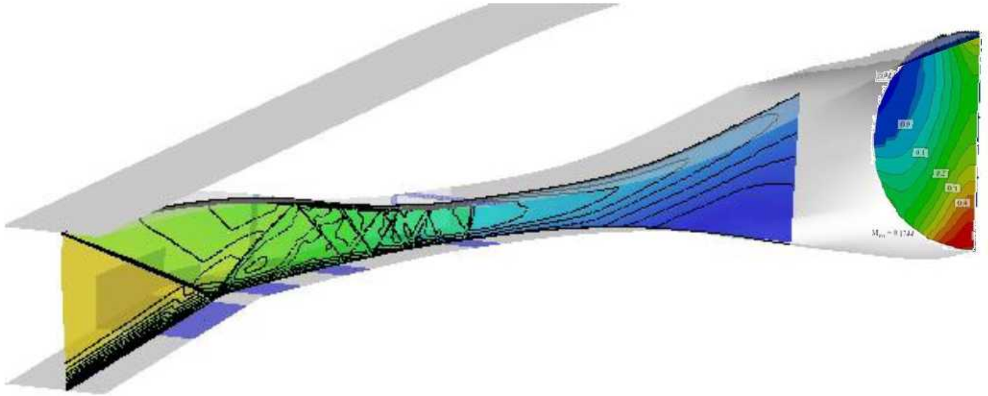
CFD highlights flow features that can guide hardware options and test planning

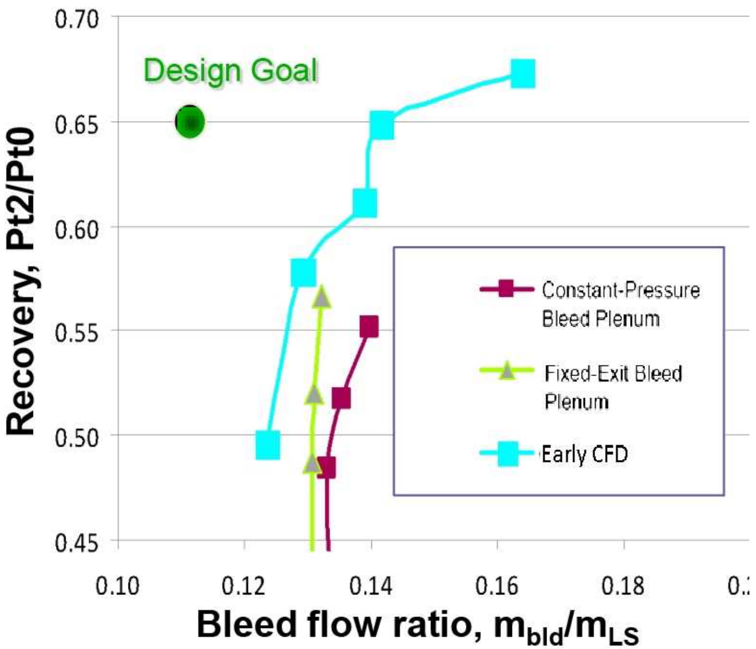
Low – speed flowpath CFD (Slater)

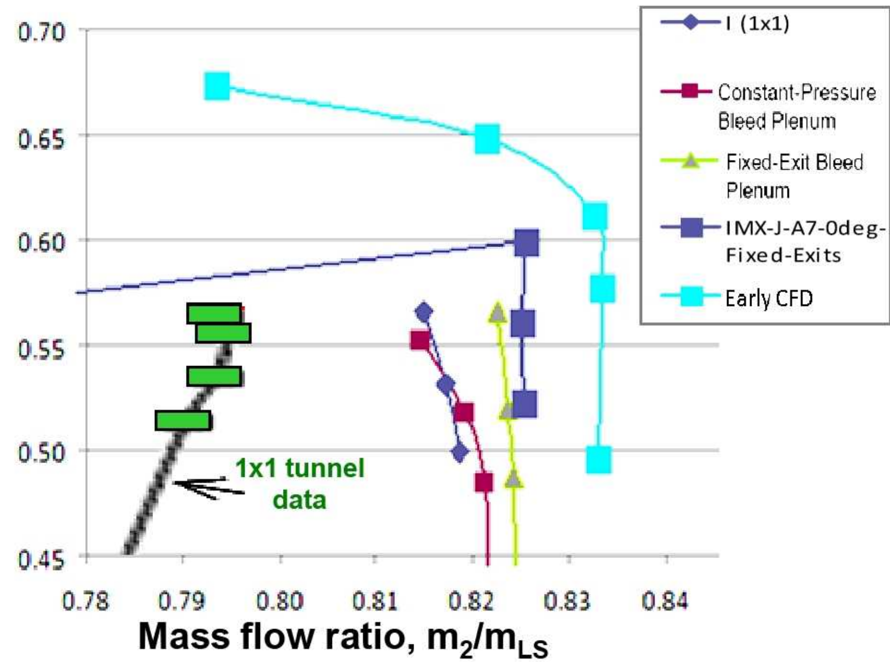


Back-pressured CFD Study: Performance ‘Cane’ Curves

- Low-Speed Inlet Performance
- 1x1 SWT Run 21 bleed configurations
- Distortion from CFD is high
- New modeling for bleed plenum b.c.’s
- Bleed A7 seems best for LIMX





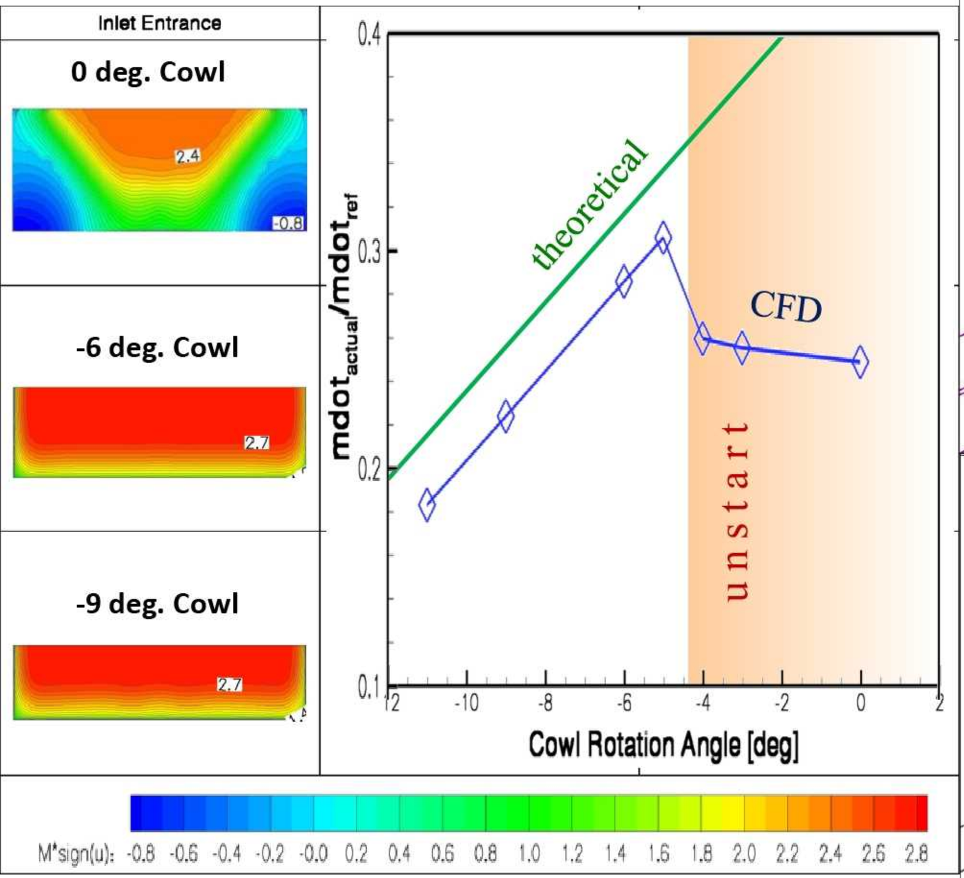


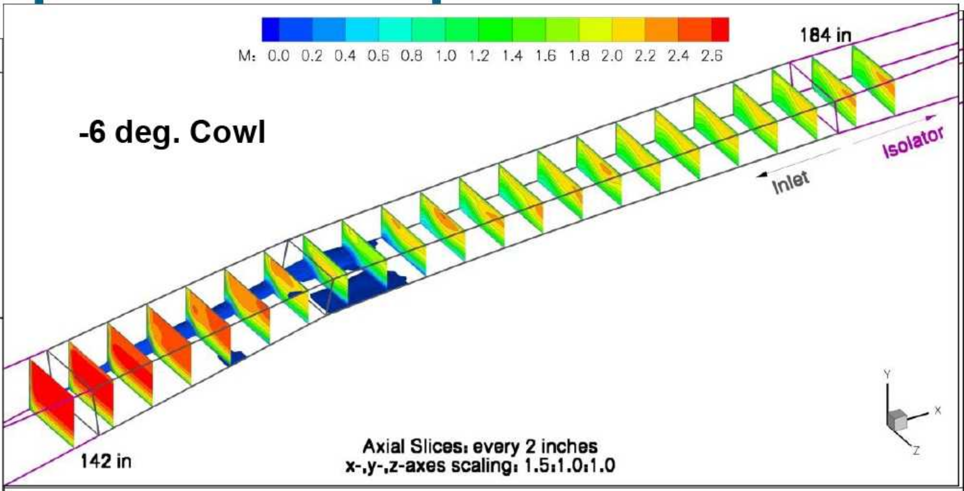
CFD suggests LS recovery perf. is near goal, AIAA being prepared

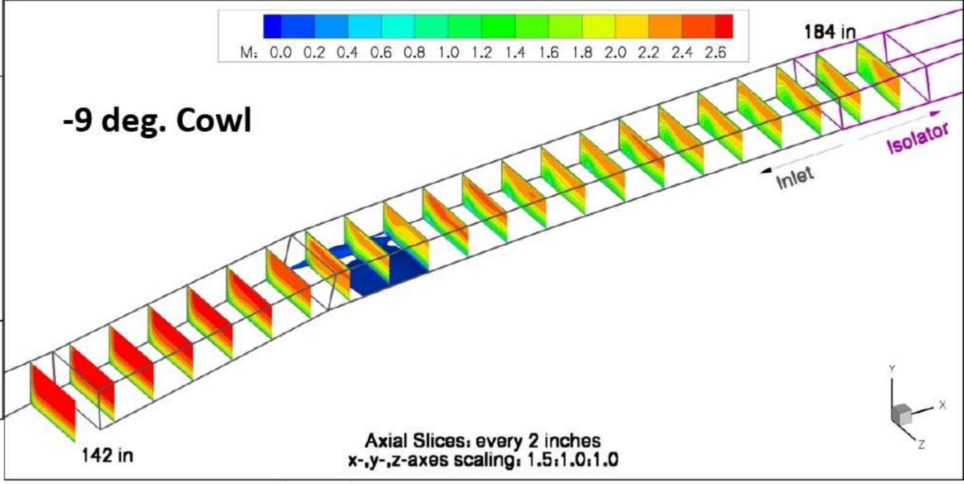
High speed flowpath, Cowl Rotation (Dippold)

Low-speed closed

Mach Contours Through HS Flowpath - No Backpressure





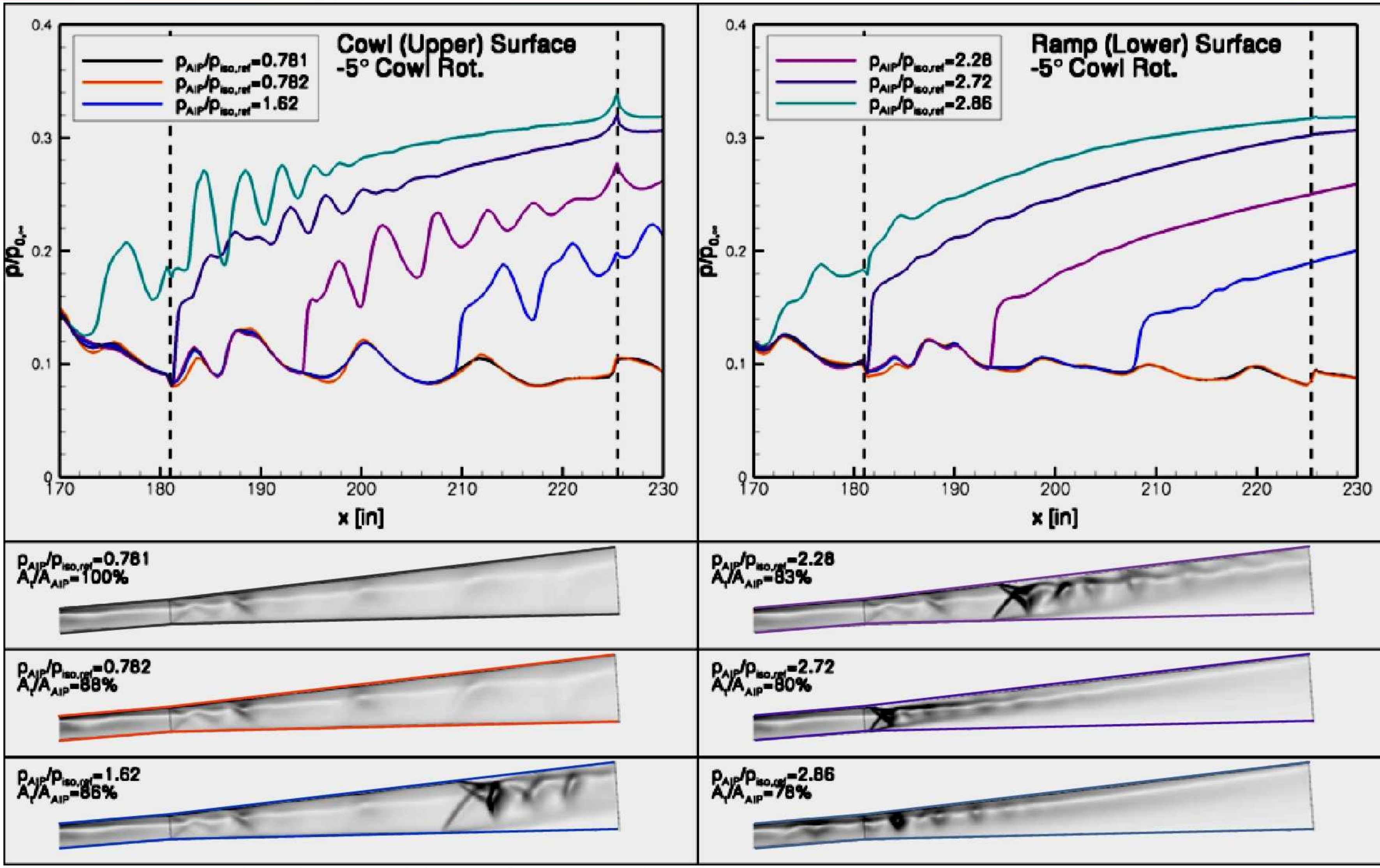


- Significant corner flow separation observed for +2 to -6 HS cowl angles
- Minor flow separation observed for -9 and -11 HS cowl rotation angles

HS CFD suggest strong 3D effects, and unstart around -5 deg.

High speed flowpath (Dippold)

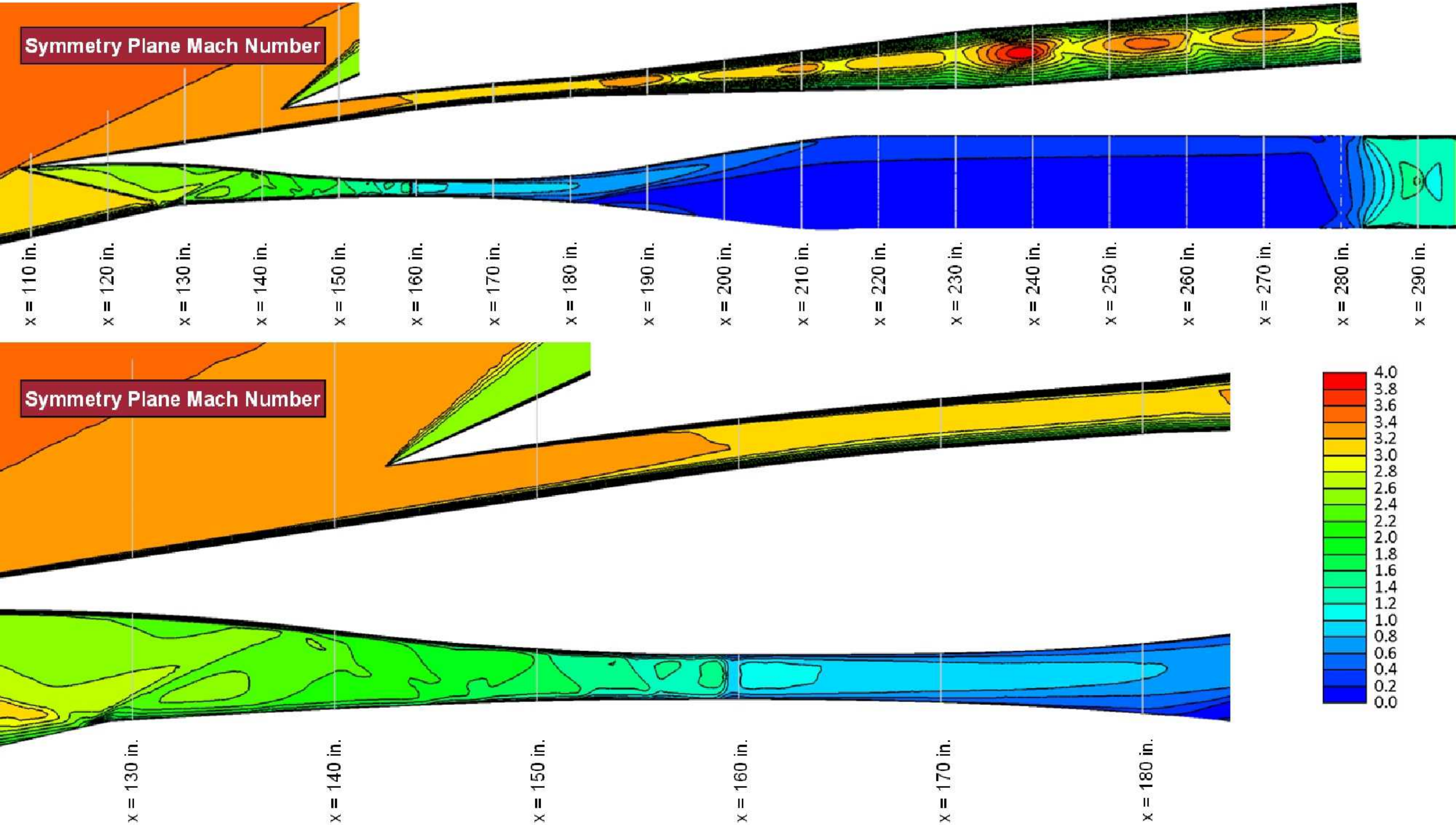
Surface Pressure and Schlieren Plots: -5° Cowl



- Dashed vertical lines denote isolator region

Sample of Boeing's CFD for CCE-LIMX

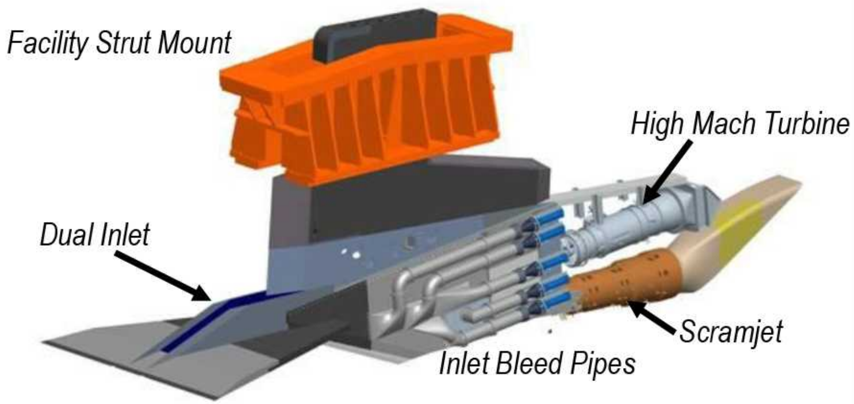
Case 018_173_041.17 - LS Cowl Angle = 0.4°; HS Cowl Angle = 0°; Ramp Angle = 12.5°



David Witte coordinates Boeing's CFD efforts

Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, how, when, who, why?
- Inlet Design / small-scale test
- CFD predictions
- Test Planning
- Instrumentation
- Summary



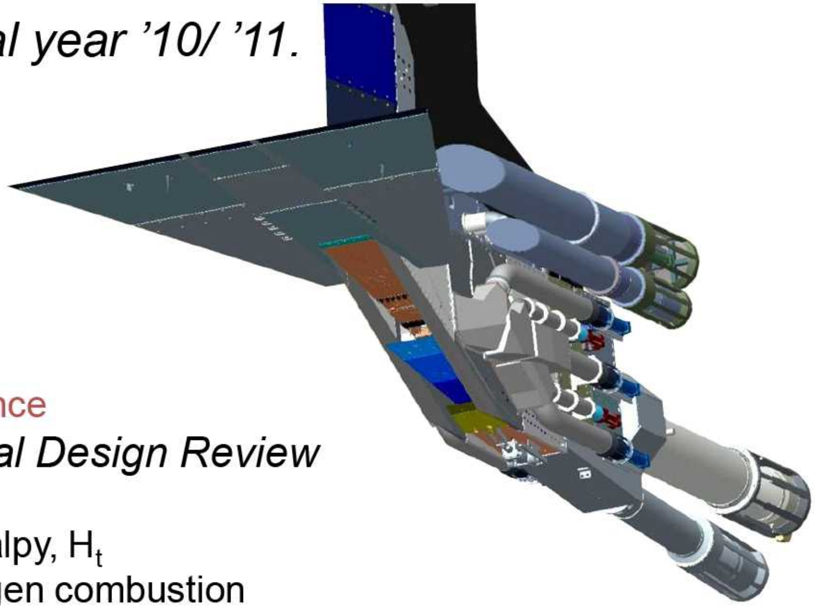
CCE Mode-X: overall test plan

Four+ phases – *three year test program* – cost dictated schedule

1. Inlet Characterization – *fiscal year '10.*
    - Performance at Mach 4 and 3 design points
    - off-design mapping (Mach and Angle-of-attack)
    - inlet mode transitions scenarios
    - simulated engine mode transition sequences

Controls research and development – *fiscal year '10/ '11.*

2. System Identification of inlet dynamics
3. Controls development and implementation



4. Engine Integration
    - Turbojet – *fiscal year '11 / '12.*
        - Limited life WI bypass turbojet
        - Representative mode transition sequence
    - Scramjet integration – *funded through Critical Design Review*
        - Fabrication and Testing are Unfunded
        - Tunnel dynamic pressure, q, and enthalpy, H_t
            - covers lower envelope for hydrogen combustion
            - Requires tunnel enhancements for higher q, H_t typical of endothermic hydrocarbons

A methodical approach that maps a course towards CCE Mode transition

CCE Mode-X: Possible scenarios

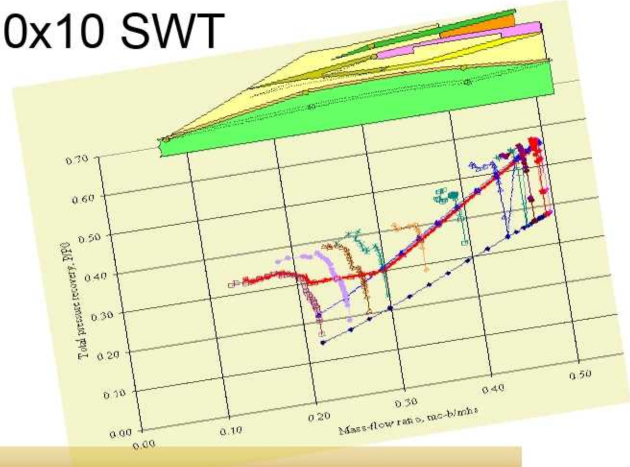
Inlet Characterization – simulated engine mode transition sequences

- Small-scale inlet test indicates:
  - Well behaved turbine flow characteristic during splitter cowl reduction.
  - Distortion and high-speed inlet operability await Large-scale tests.

- Time frame for mode transition and sequences will be investigated
  Inlet transient timed to:
    - Turbine spool down: (balanced thrust transient)
    - Turbine inlet 'slammed shut': (thrust transient causes pinch)
    - Turbine synced for acceleration: (excess thrust transient)
    - High-speed flowpath operability constraints?

- Other transient effects that can be investigated in 10x10 SWT
  - Angle of attack changes, (low frequency)
  - Mach number changes, (low frequency)

- Understand inlet dynamics for basic inlet control
  - Normal shock / bypass
  - Bleed/cowl/ramp scheduling
  - Restart control, (lower priority)

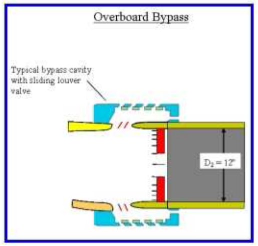


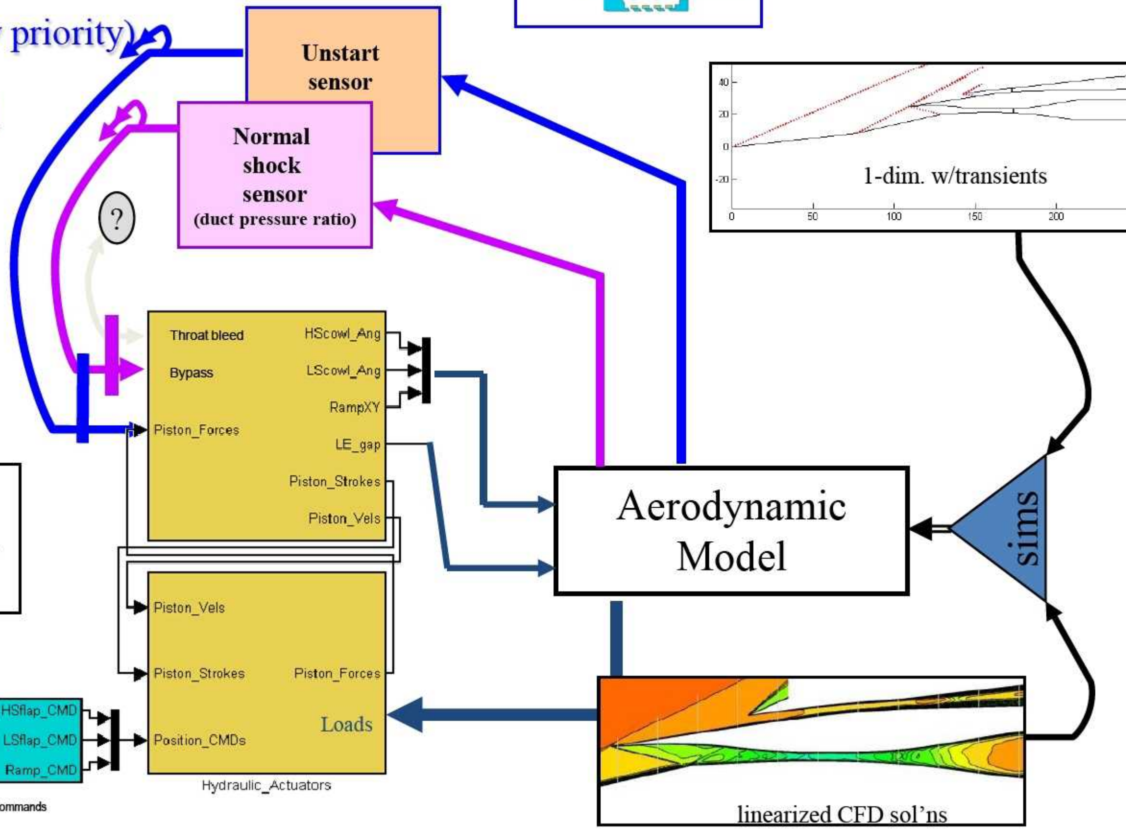
Detailed planning for mode transition scenarios has begun

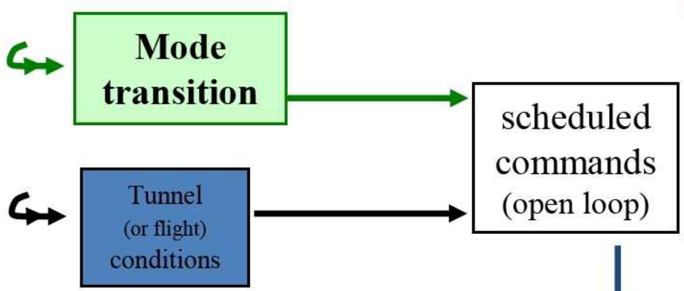
Controls Tests for Inlet Mode Transition

Control composed of four loops: [listed from inner to outer]

1. Pressure-rise control
   - Low-speed inlet normal shock
   - High-speed isolator
2. Inlet unstart recovery (low priority)
3. Inlet mode transition
4. Inlet geometry configuration = f(Mach, engine)



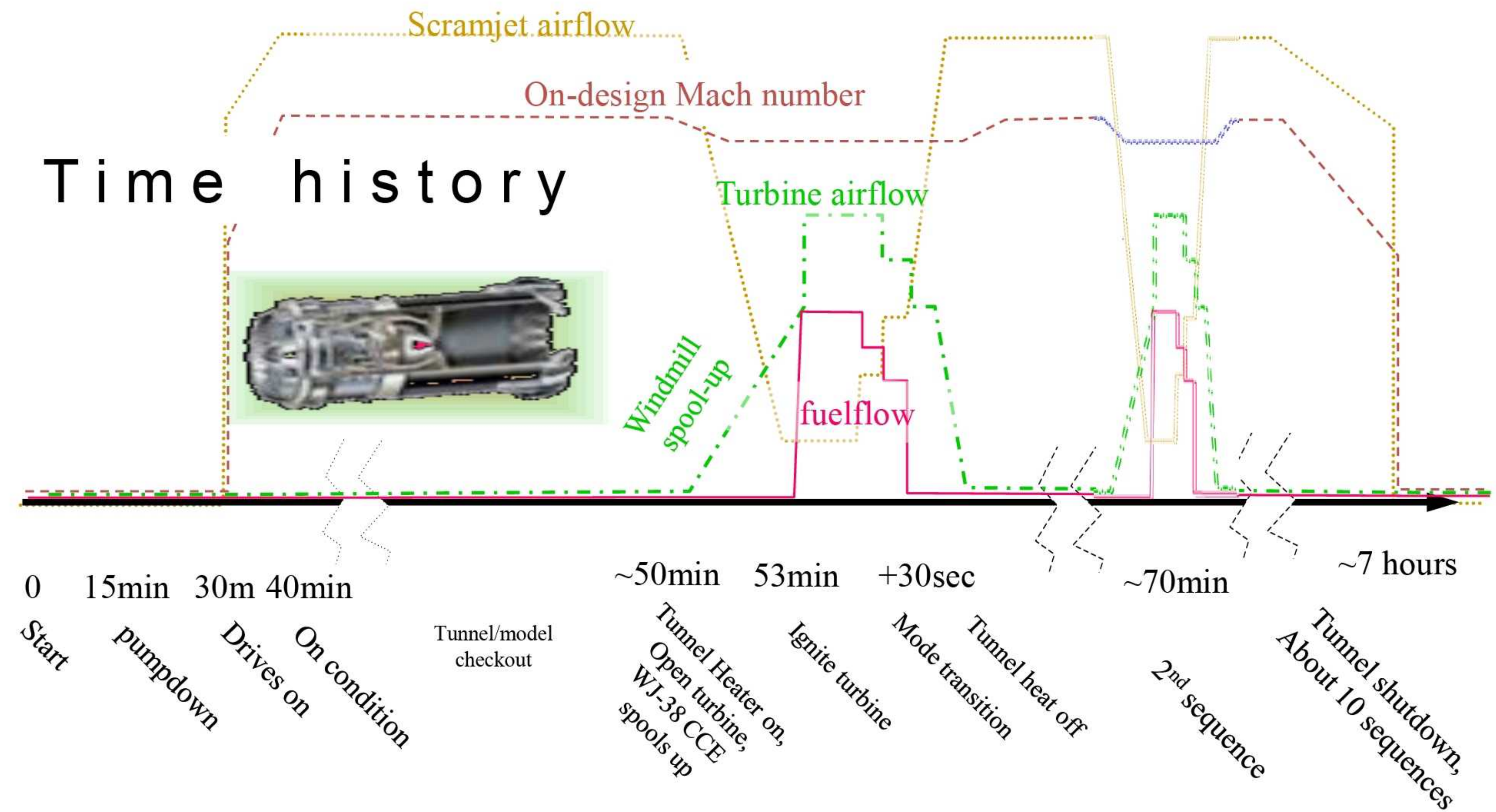




Tom Stueber is leading dynamic / controls research

CCE Mode-X: A typical tunnel run

Turbojet Engine Integration -- Representative mode transition sequence



A typical time history shows the flexibility of 10x10 for turbine testing

CCE Mode-X: inlet test plan

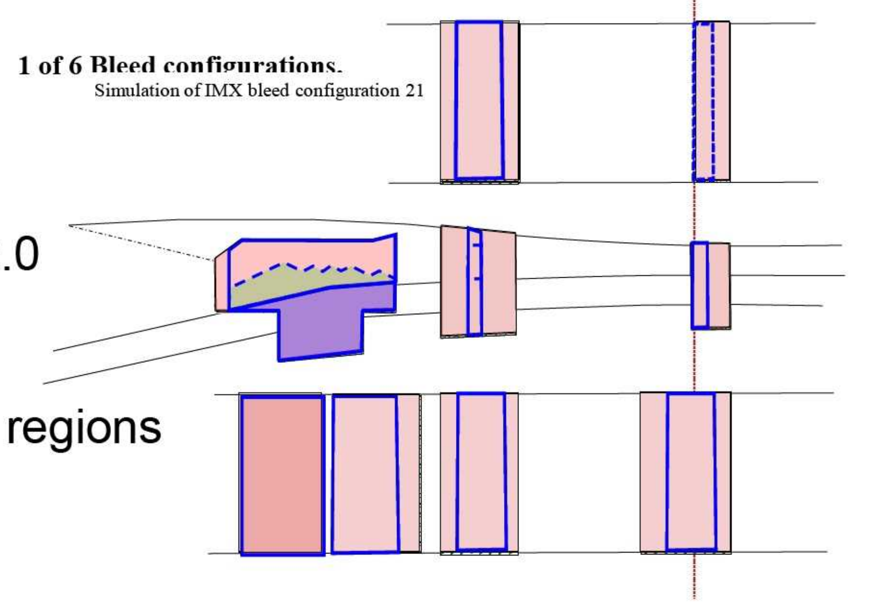
Test configurations – 6

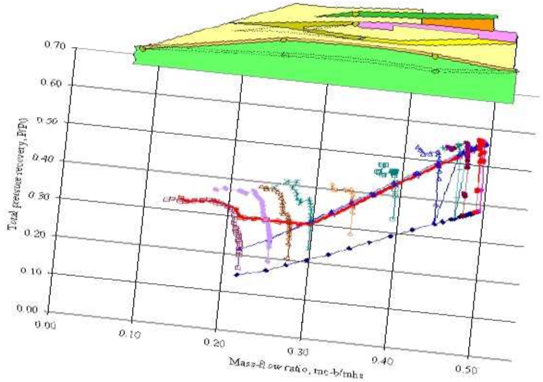
- Mode transition at Mach 4
- Mode transition at Mach 3.1
- Inlet performance at Mach 4, 3.5, 3.0, 2.5, 2.0

1. All bleed open
   - Develop bleed characteristics for bleed regions
2. All bleed open, closed forward SW1 bleed
   - 3 vortex generator configurations
   - Constant bleed plenum pressure
3. Reduced bleed configuration
4. Cowl bleed only
5. No bleed

6. Cowl lip variations

➢ **HS flowpath performance at select LS config.**

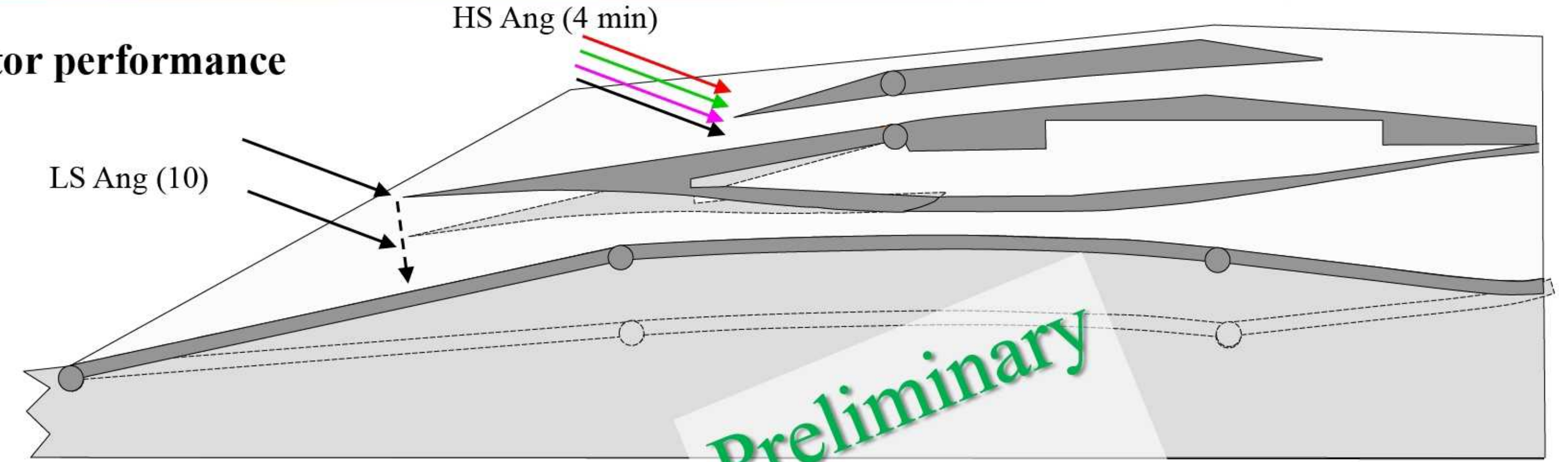


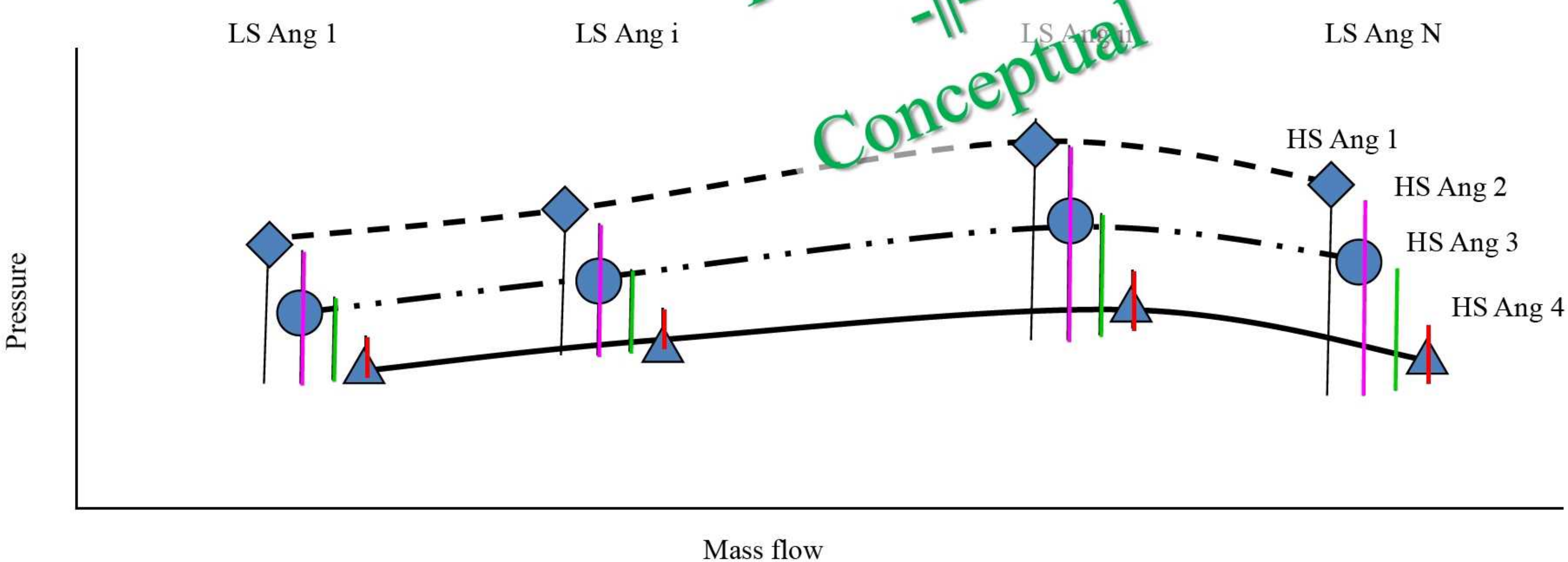


An Inlet test plan has been drafted for operational discussion

CCE Mode-X: HS inlet scenario

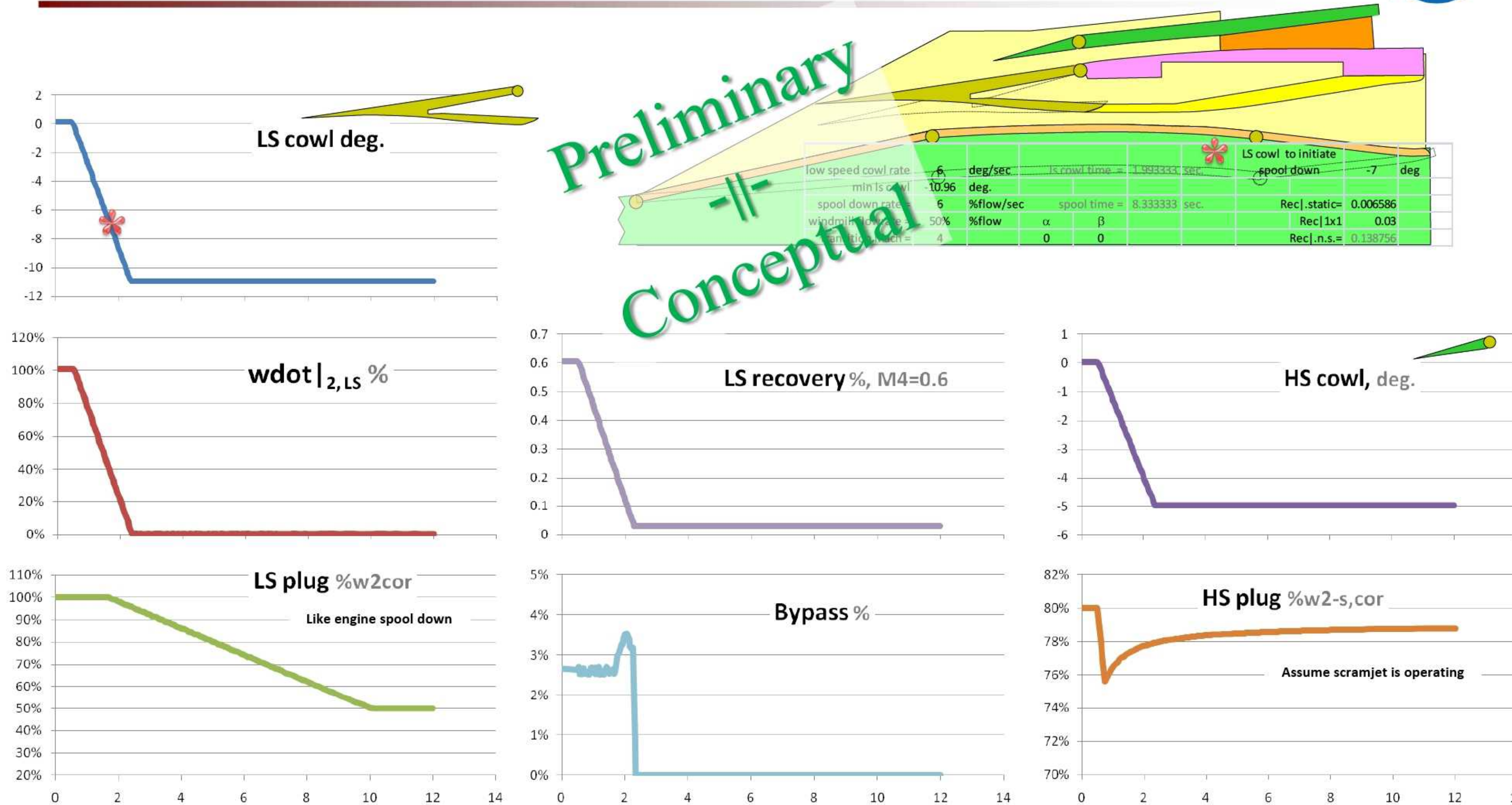
Isolator performance





High-speed inlet transition is unknown until the Large-scale testing begins

CCE Mode-X: Sample inlet time sequence

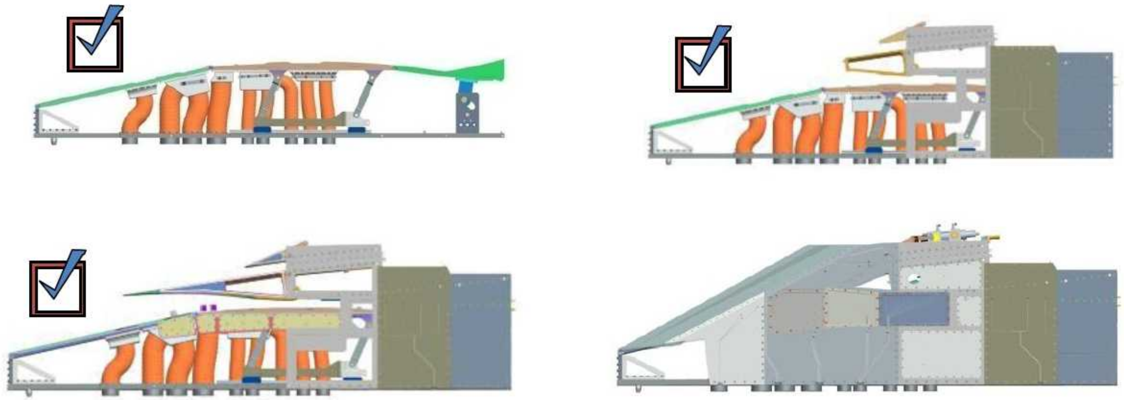


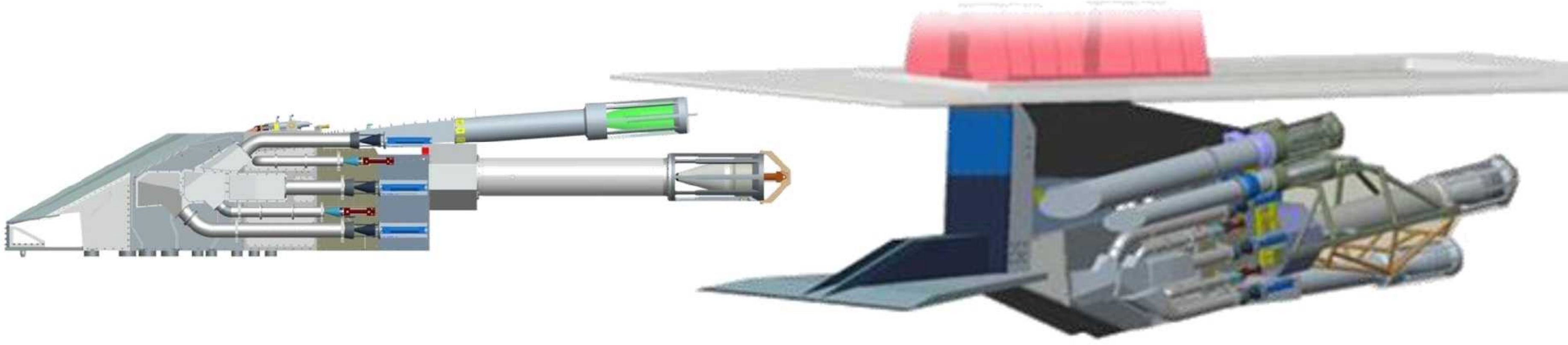
time, seconds

CCE Mode-X: Inlet Milestone

HYP.07.02.001 GRC/RTE: Inlet: Large scale (L-IMX) experiment to demonstrate mode transition. FY10 (!March, 2010)

- additional time required for design/fab of the model has delayed testing.

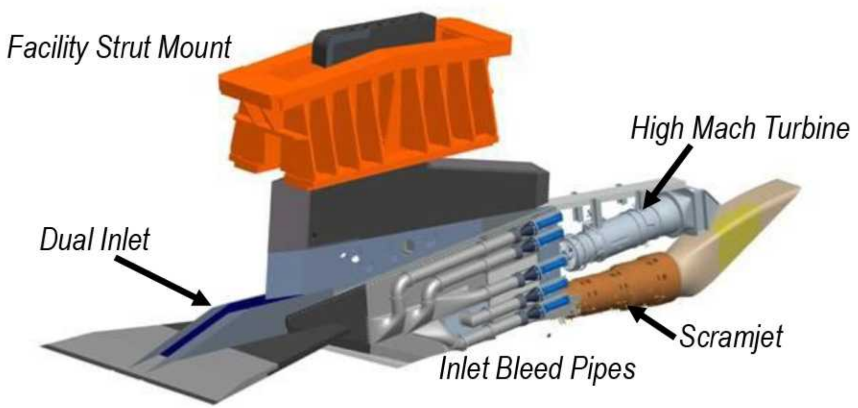




Hardware delivery delayed due to ramp actuation redesign

Outline: CCE ModeX Aero. Research / Test Planning

- Questions: what, why, how, when, who?
- Research Objectives
- Inlet Design / small-scale test results
- CFD predictions
- Test Planning
- Instrumentation
- Summary



CCE Mode-X: inlet instrumentation

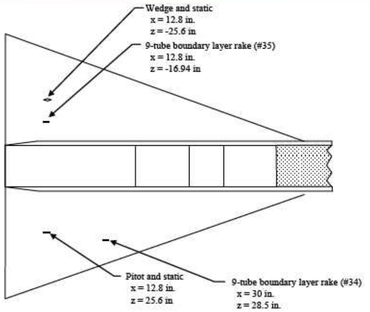
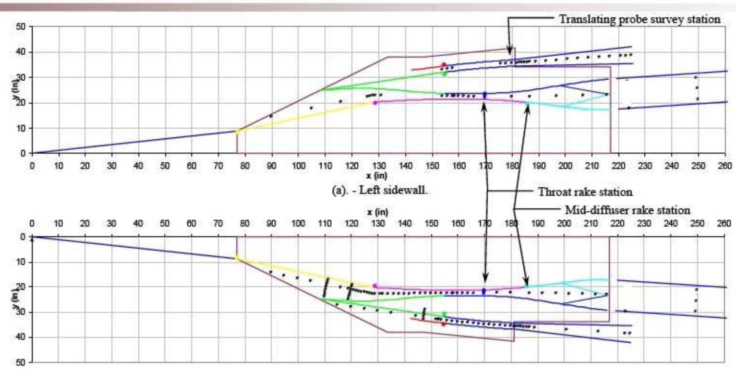
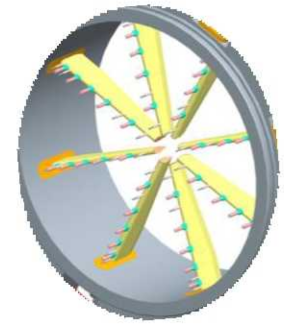


Figure 73A. - Sketch indicating locations of existing outboard Mach 5 Inlet expansion plate instrumentation.



(b). - Right sidewall.

Figure 58 – Sidewall surface static pressure instrumentation.



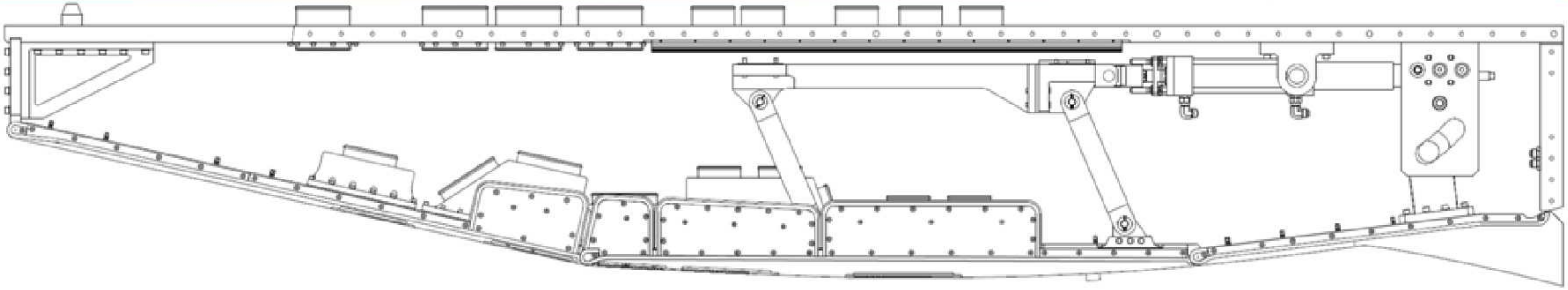
	Static	Rake	Translating Probe	Kulite	Other
High-Speed Inlet	179		2	14	
Low-Speed Inlet	242	120		17	
Low-Speed Throat	39	76			
Cold pipe	8				
Bleed Plenums					26
TOTAL	468	196	2	31	26

Not included in count:

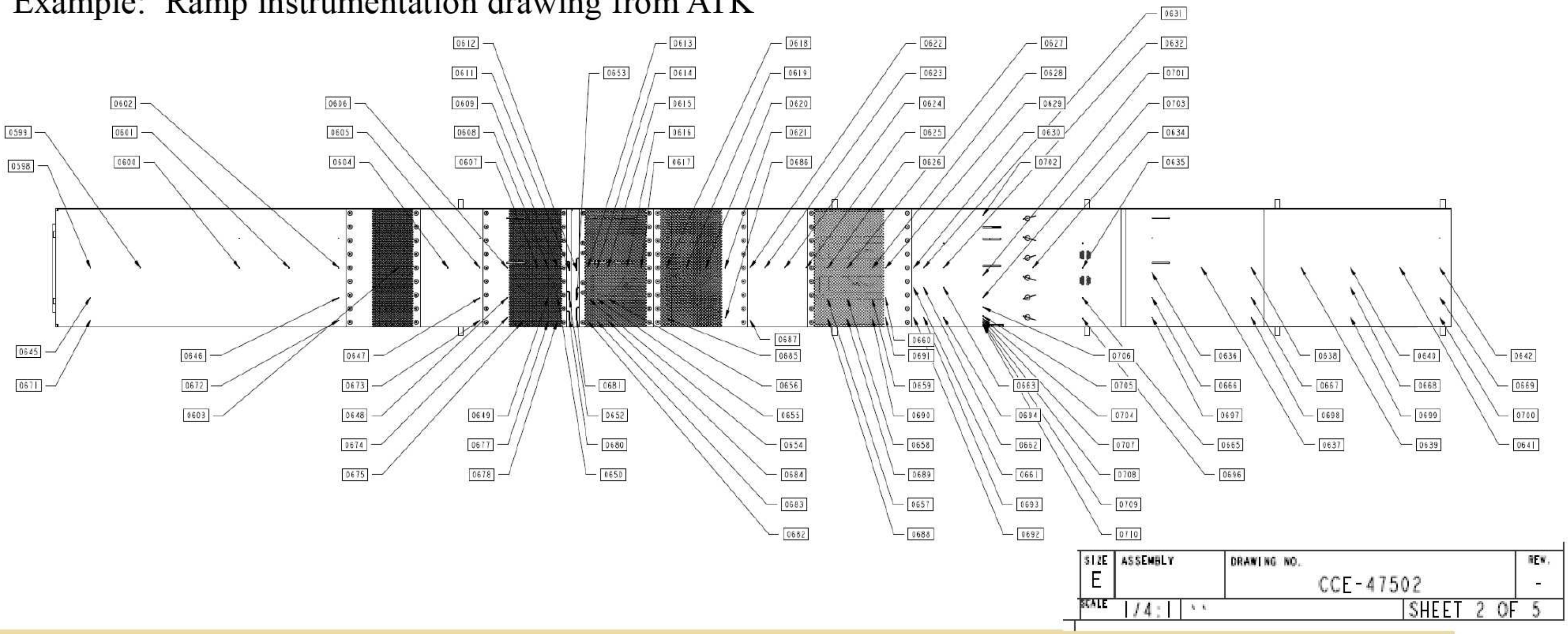
- Expansion plate instrumentation ---- rakes(22)
- High-speed inlet isolator exit instrumentation ---- statics(8?), rakes(25)
- Bleed pipe instrumentation ---- statics(~60), rakes(?)
- Low-speed inlet AIP instrumentation (VIIPAR rake array) ---- statics(8), rakes(72), kulites®(40)

Grand total: statics(544), rakes(191), x-probe(2), kulites®(71), acceler(12), other(26)

CCE Mode-X: inlet instrumentation



Example: Ramp instrumentation drawing from ATK



Instrumentation drawings are underway, computing in development

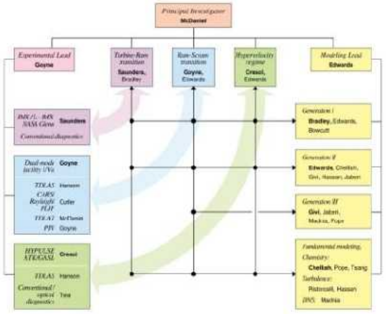
Center Goals

(National Center for Hypersonic Combined Cycle Propulsion)

Focus Area 2: Benchmark data sets for RANS, hybrid LES/RANS, and LES models
- high- and low-frequency wall static and dynamic pressures
- flowfield rakes, mass flow measurements and schlieren.
- focus on *second-generation* hybrid LES/RANS numerical methods

Focus Area 3: Performance improvements and control of mode-transition
- control schemes for the turbine to ramjet transition
- actual turbine engine to be installed in the low speed flowpath

Preliminary schedule:
- year 1: Collaboration of NASA and center teams, Inlet testing
- out years: Controls testing, turbine engine testing



CCE / LIMX = **C**ombine **C**ycle **E**ngine / **L**arge-scale **I**nlet **M**ode Transition

CCE Mode-X October 1st Summary

- A rational plan to address Combine Cycle Engine mode transition has been planned with fabrication underway and testing planned for early 2010.
- The 10x10 SWT provides a unique facility to address large-scale testing for this mode transition research and demonstration.
- Full-scale HiSTED-class turbines such as the modified WI WJ-38 has been incorporated. SLS Tests of Engine/ Nozzle planned late summer at WI. Plans are in place for integrated Mode-X testing with modified WJ-38 in 2011/12.
- The 10x10 SWT has tested large supersonic turbines like the J-85, TF-30 engines. The tunnel's maximum engine size is nominally a J-58, ~50" diameter engine.
- Turbine engine and high-speed propulsion expertise at NASA provides the depth and large facilities (10x10, 8x6 SWTs, 8'HTT and PSL) to address critical need for CCE mode transition research.

NASA Hypersonics project will address key elements of CCE mode transition

BACK-UP CHARTS

- Objective statements
- Air-breathing propulsion modes
- Conceptual Geometry
- 1x1 IMX results (from JANNAF)
- Old test plan charts, (Techland has new ones)
- Mech. Design / Tunnel layouts
- Teaming: to date + NCHCCP / UVa
- Instrumentation conceptual layout
- Project charts (Suder) + issues from April, during Jim Pittman visit
- Recent fabrication issues
- Translating cowl
- Boeing CFD
- Distortion
- Ramp actuation redesign??
- 1x1 IMX High Speed video sequence (external, separate ppt file)

- John's CFD charts for Bremen
- Other test activities
    - 15x15 isolator
    - 1x1 plans / AFRL
    - bleed experiments
- Isolator performance, Istar experience
- 10x10 control room and staffing

Air-breathing Combined Cycle Propulsion Modes

Vehicle Design

TSTO

SSTO

Flight Conditions

M_{inf}

Altitude
- q, Ttot, Po

Mstart ~2

Mtrans ~ 4

Mstage ~ 7

AoA ~ 4°

Yaw ~ 0°

P e r t u r b a t i o n s

Propulsion Flowpath

TBCC
- **overunder**
- cocooned

RBCC
- single flowpath

Inlet Config.

Low-speed
- mixed/ext. compression
- Mach throat~ 1.3
- var. geom.
- turning
  - Inward
  - Rect.
  - Axi.
- bleed

High-spd
- Mach throat ~1/2 M_{inf}
- var. geom. ??
- turning
  - Inward
  - Rect.
  - Axi.
- isolator/bleed

P e r t u r b a t i o n s

Engine Aspects

Turbine
- dry
- afterburner
- stall ?
- windmill ?
- fuel type -HC

Ram/Scram
- Fuel stage ?
- var. geom. ?
- Mach ignite ?
- fuel type
- cross-section -circle

Beamed
- . . .

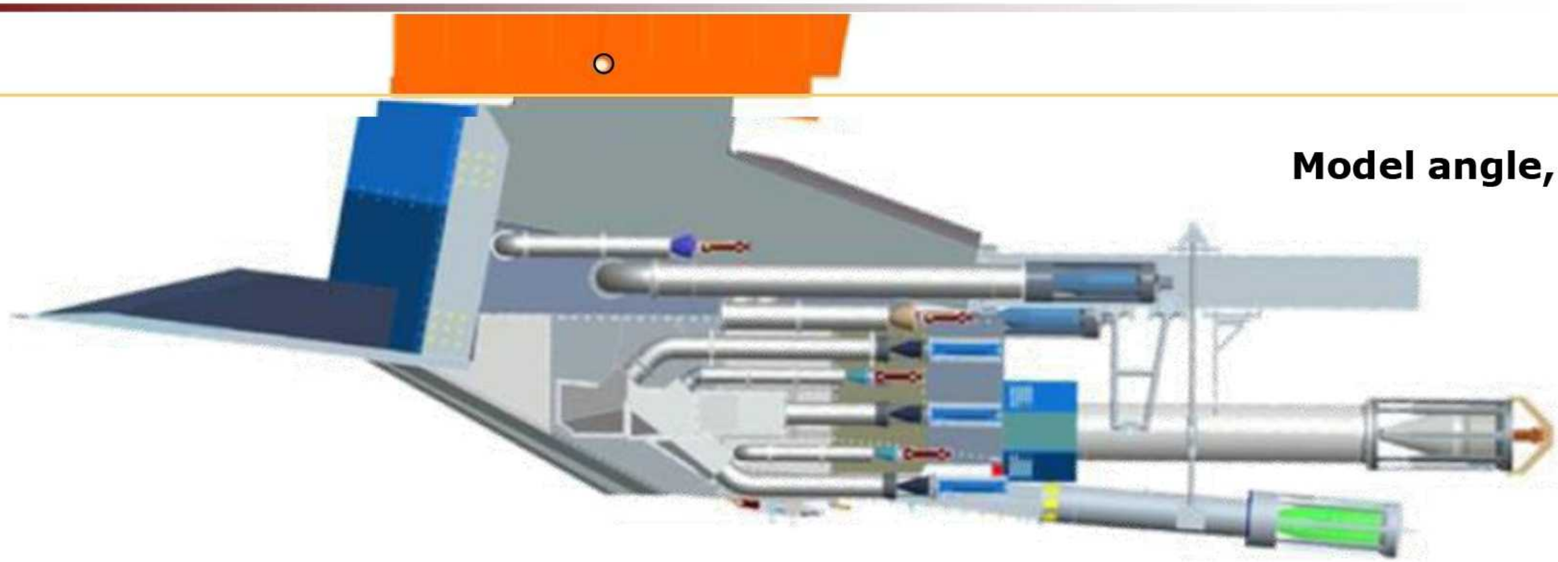
Nozzle Aspects

Low-speed
- var.geom.
- ejection
- ext. burn
- tail rockets

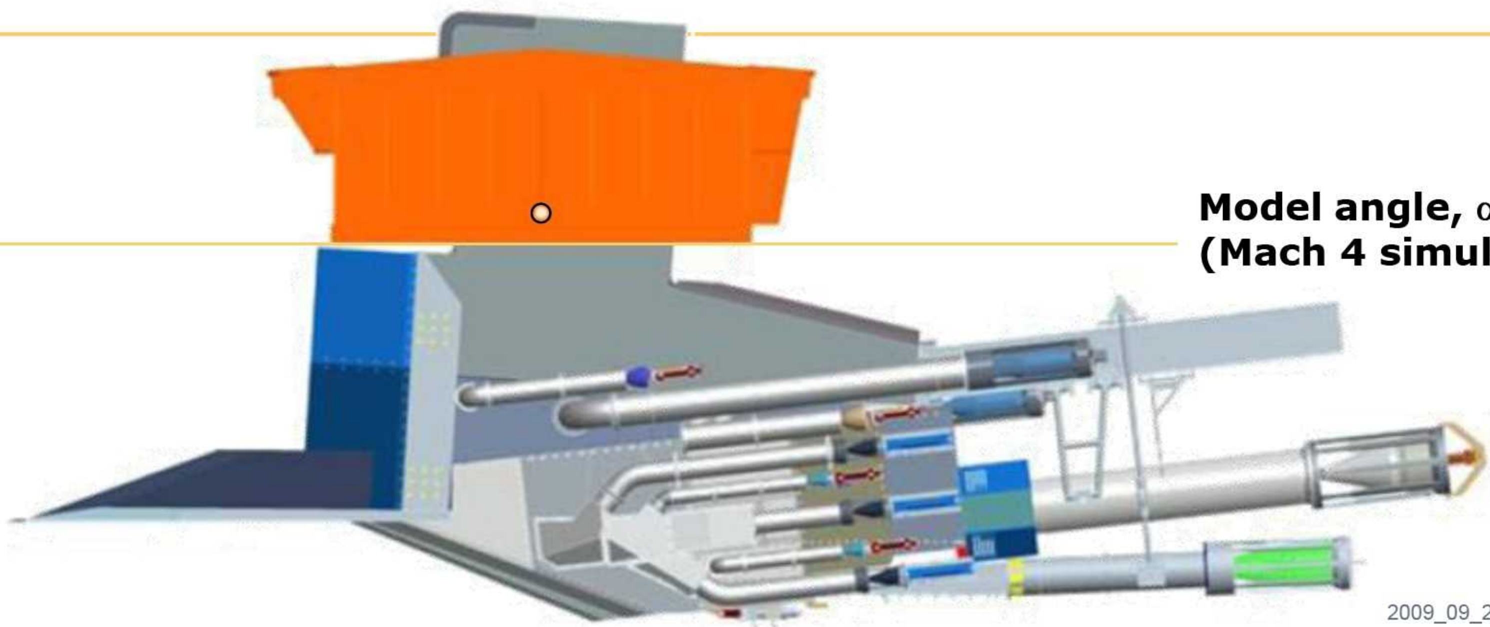
Scram
- fixed ?
- variable geo.

CCE Design is a subset of mode variation

Orientation for Mach 4 simulation in 10x10 SWT



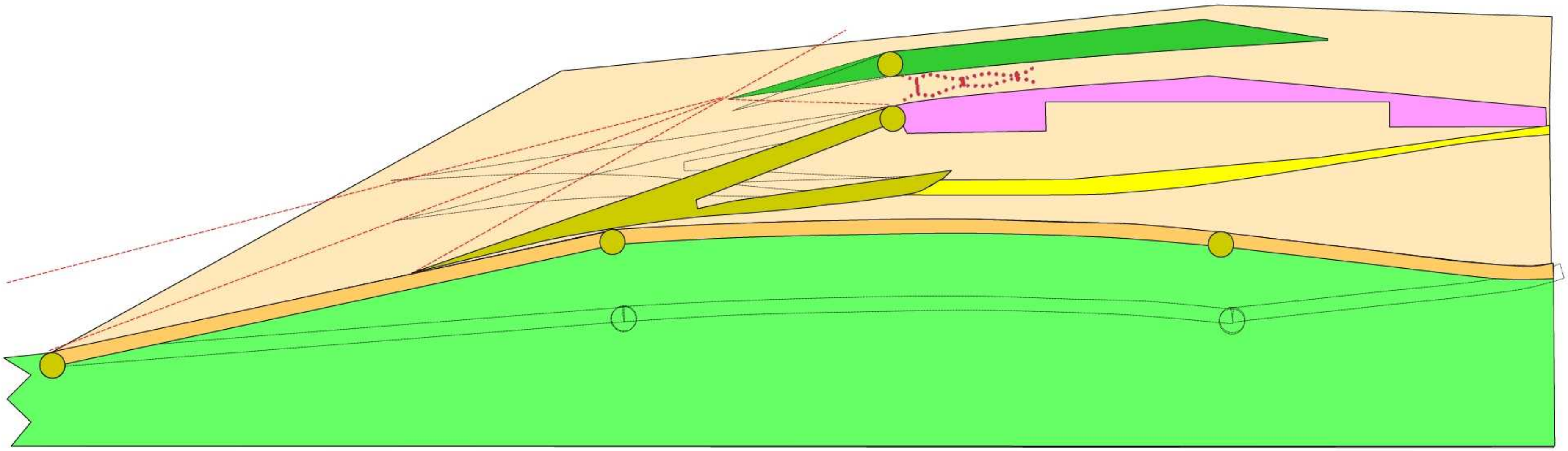
Model angle, α = 0º



Model angle, α = -7º
(Mach 4 simulation)

Mach number / mode transition with shocks

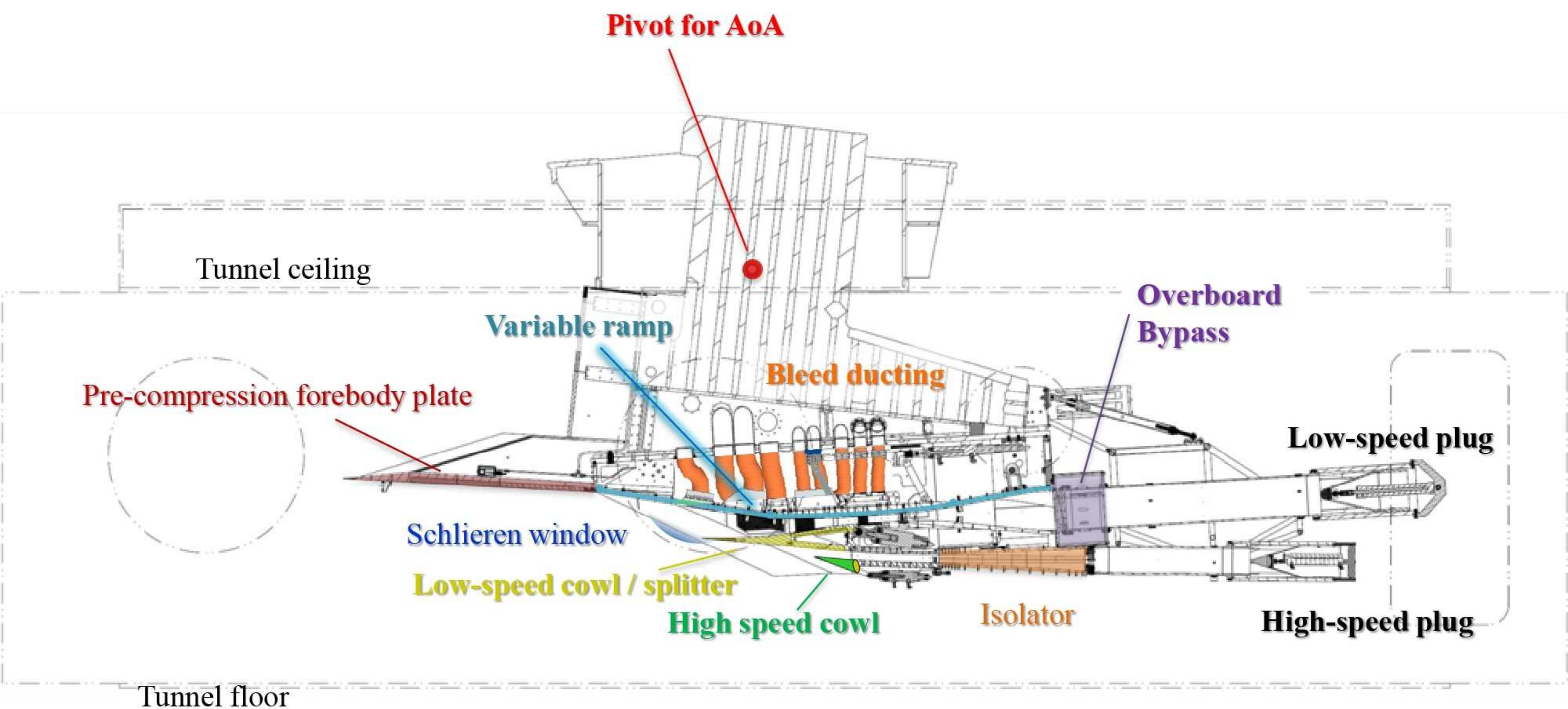
M = 7 low-speed closed.



Mode transition sequences

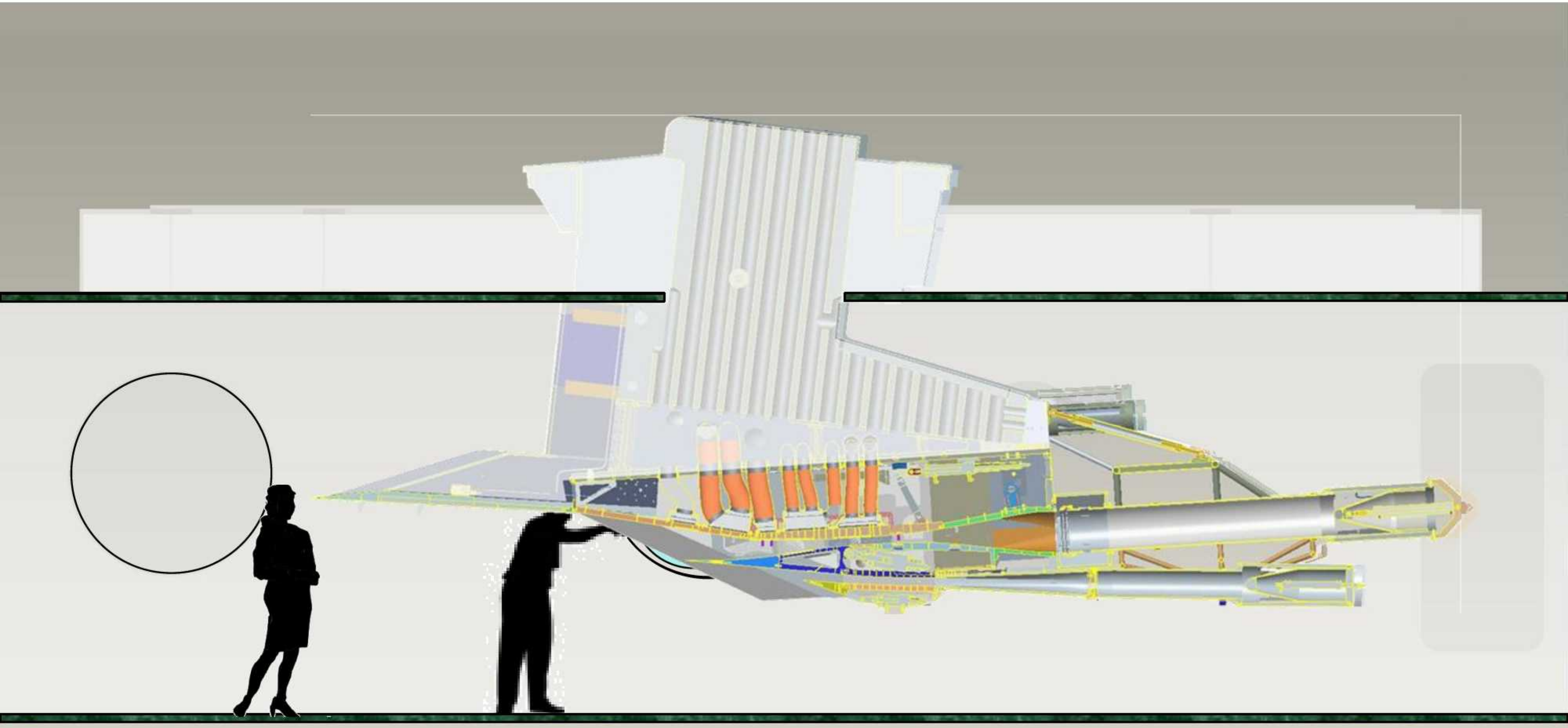
Variable geometry ramp inlet configurations.

CCE-LIMX: Key model elements



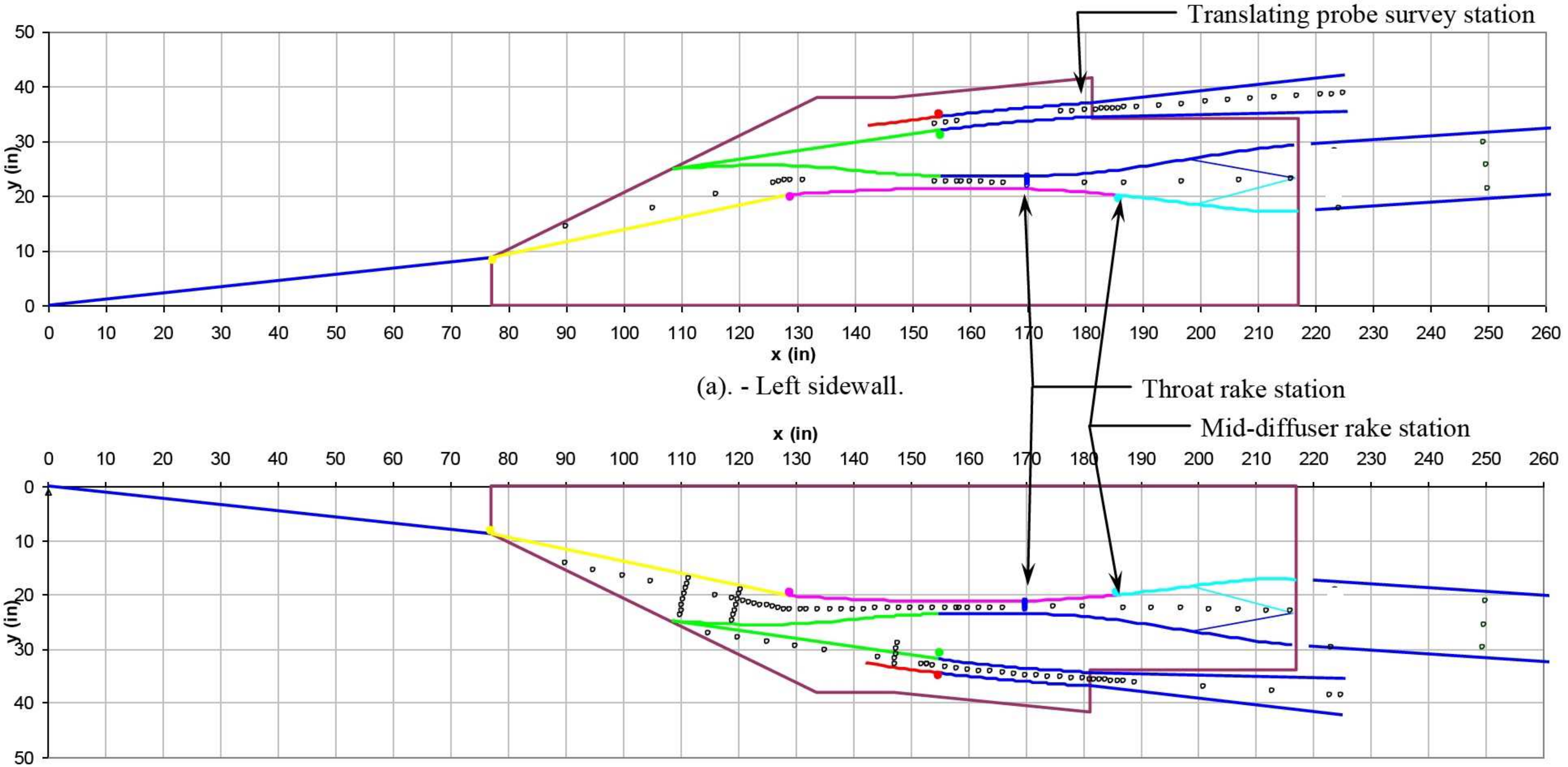
Variable geometry in **Bold**

CCE – Large scale Inlet Mode Transition model



10x10 SWT Installation, original position

TBCC-LIMX: instrumentation

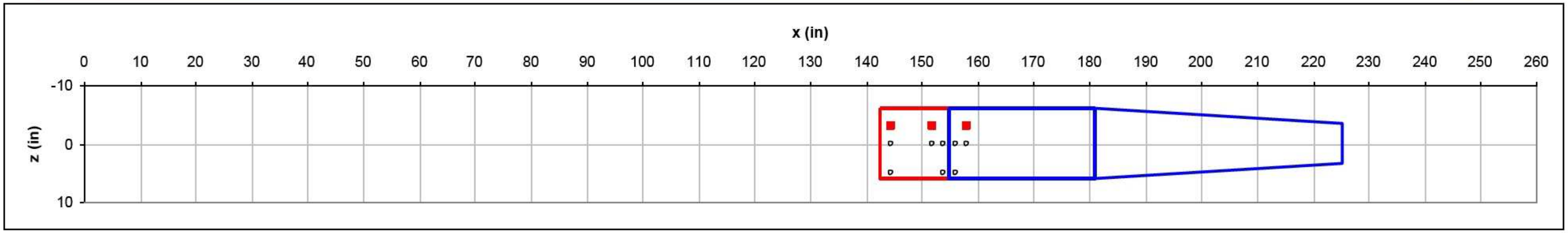


(a). - Left sidewall.

(b). - Right sidewall.

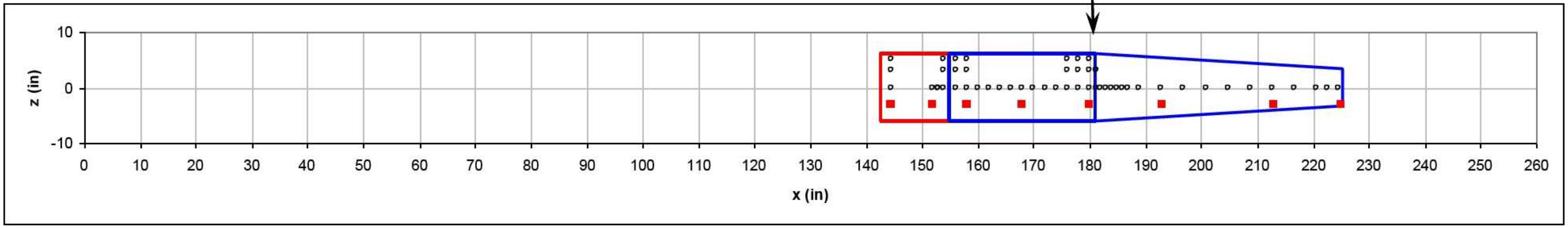
Sidewall surface static pressure instrumentation.

TBCC-LIMX: instrumentation

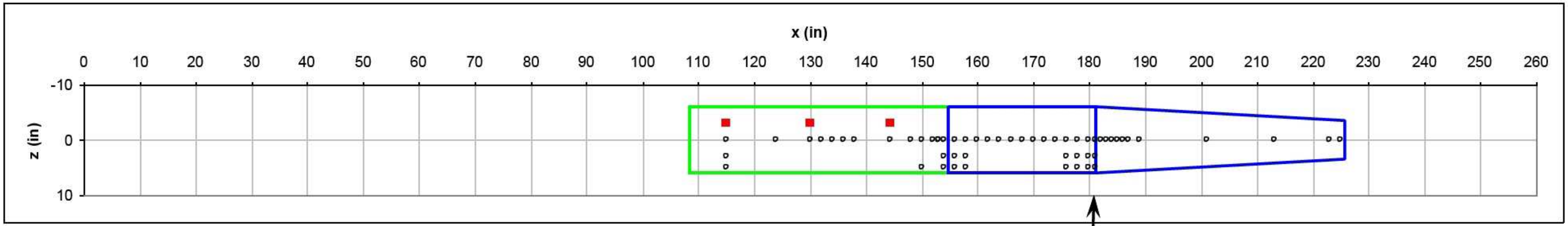


(a). - Cowl (exterior).

Translating probe survey station



(b). - Cowl (interior).

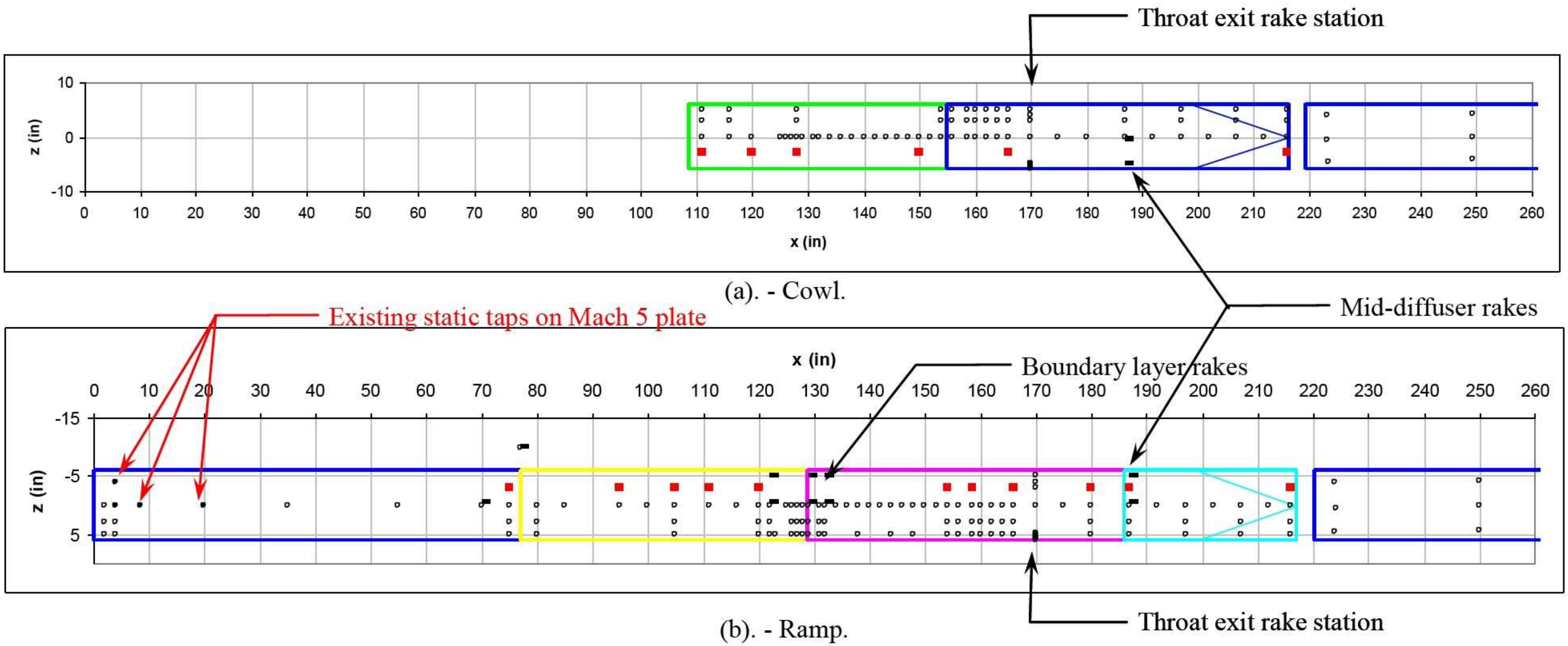


(c). – Ramp.

Translating probe survey station

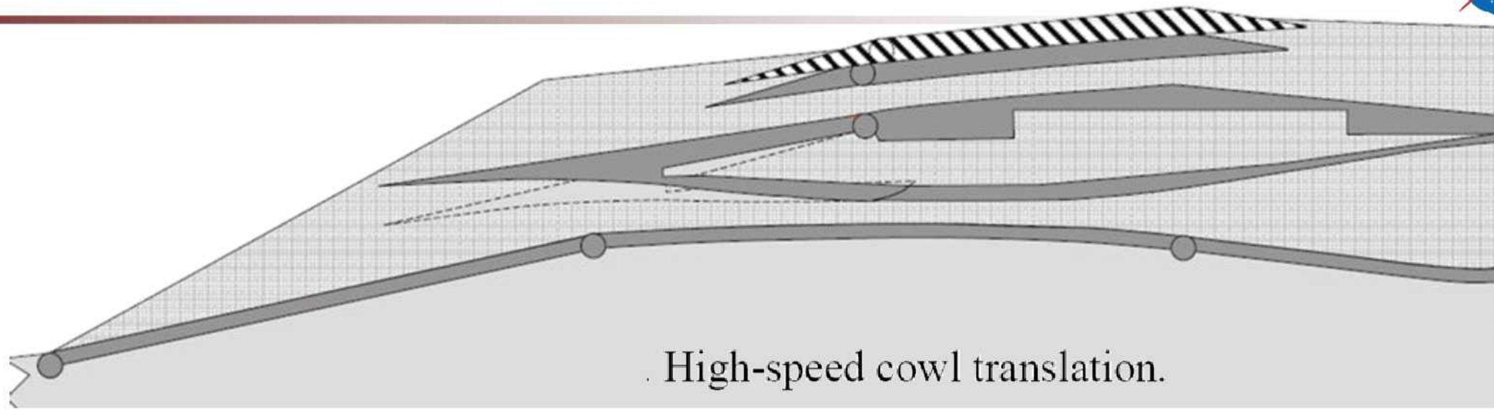
High-speed inlet surface static pressure instrumentation.

TBCC-LIMX: instrumentation

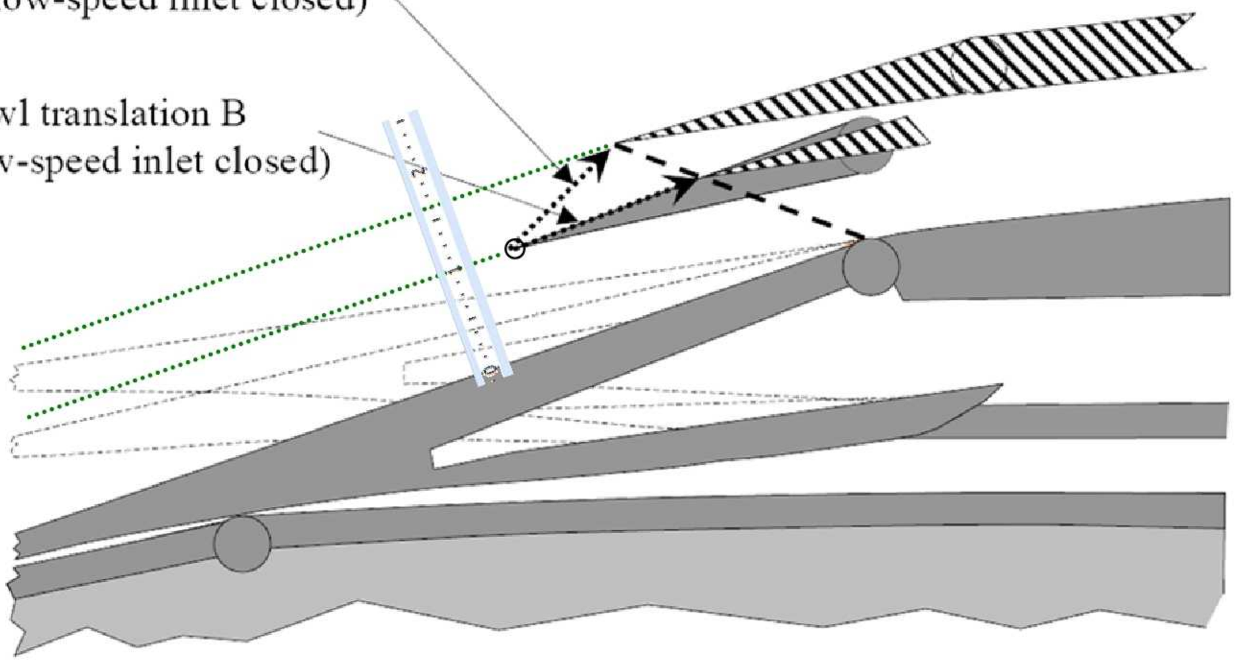


Low-speed inlet surface static pressure instrumentation.

CCE LIMX translating high-speed cowl



. High-speed cowl translation.

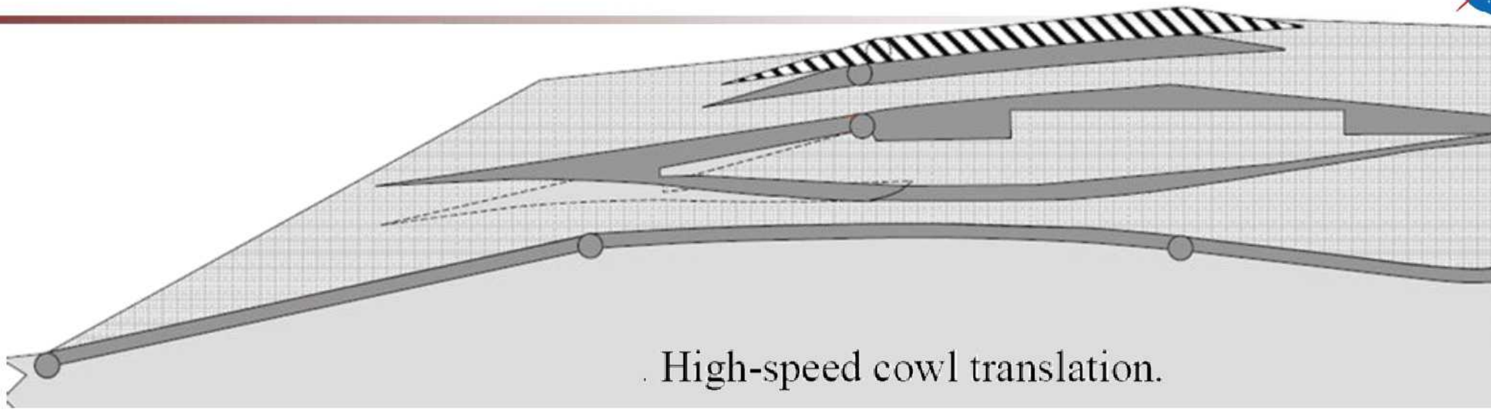


Possible high-speed cowl translation schedules.

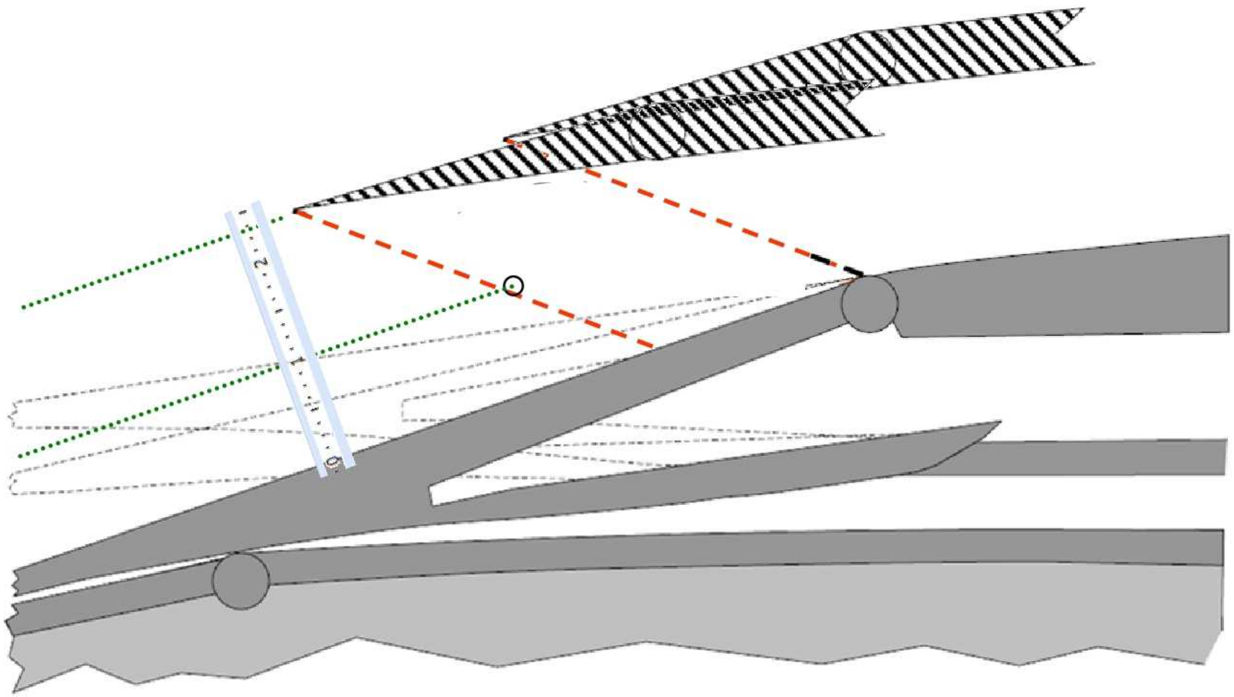
60% increase in high speed capture for 'translation A'

From:
CR-2008-215214

CCE LIMX translating high-speed cowl



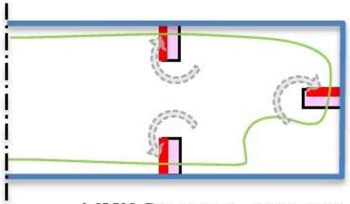
. High-speed cowl translation.

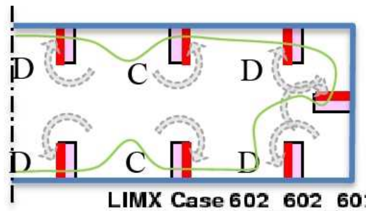


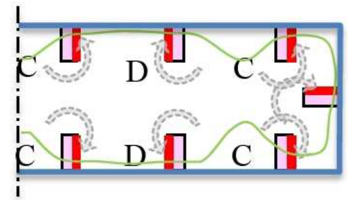
Possible high-speed cowl translation schedules.

125% increase in high speed capture for more aggressive translations

Vortex generator effects, (Boeing CFD)



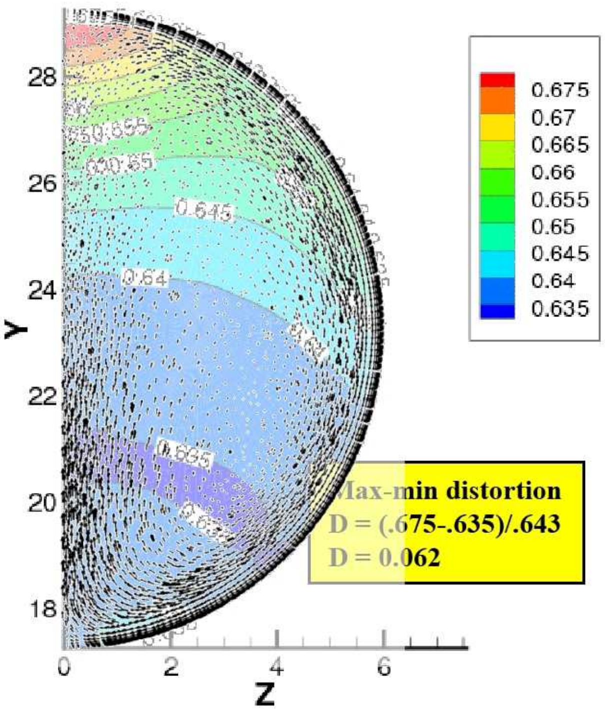




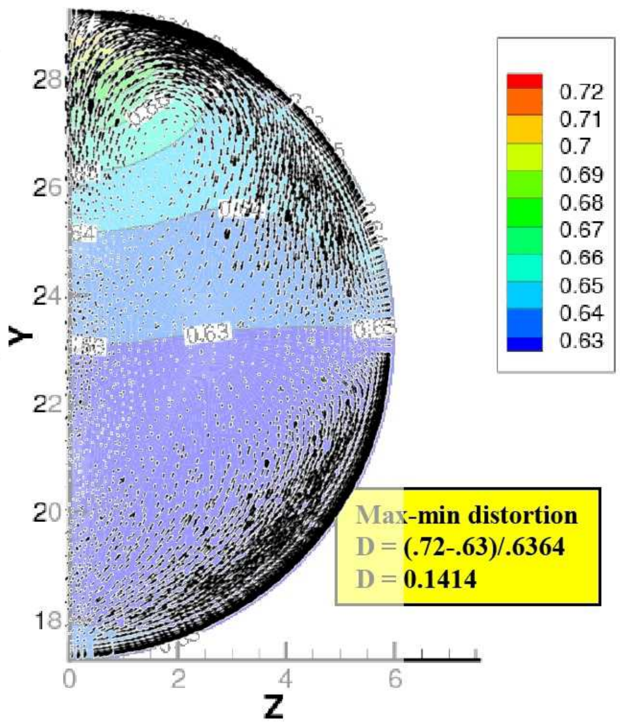
LIMX Case 001_143_001.18
Recovery at Low Speed AIP; Average = 0.6430

LIMX Case 602_602_602.7
Recovery at Low Speed AIP; Average = 0.6364

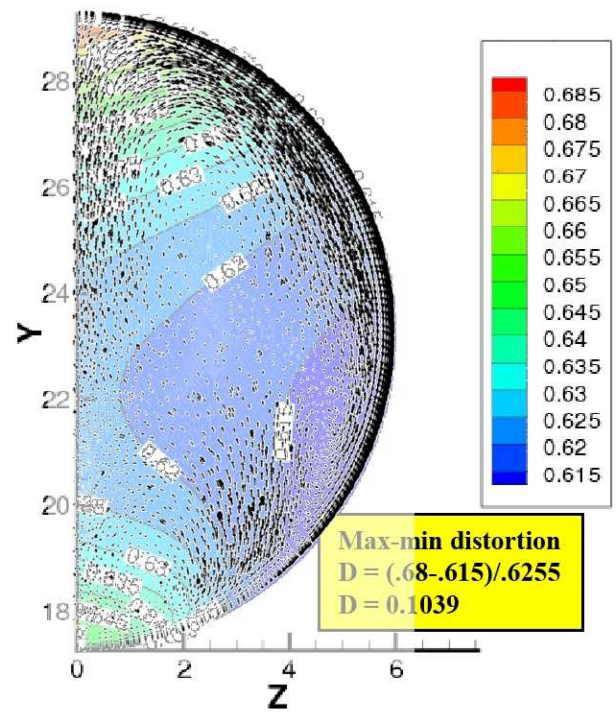
LIMX Case 601_601_601.6
Recovery at Low Speed AIP; Average = 0.6255



AIP flow field for Basic VG Configuration

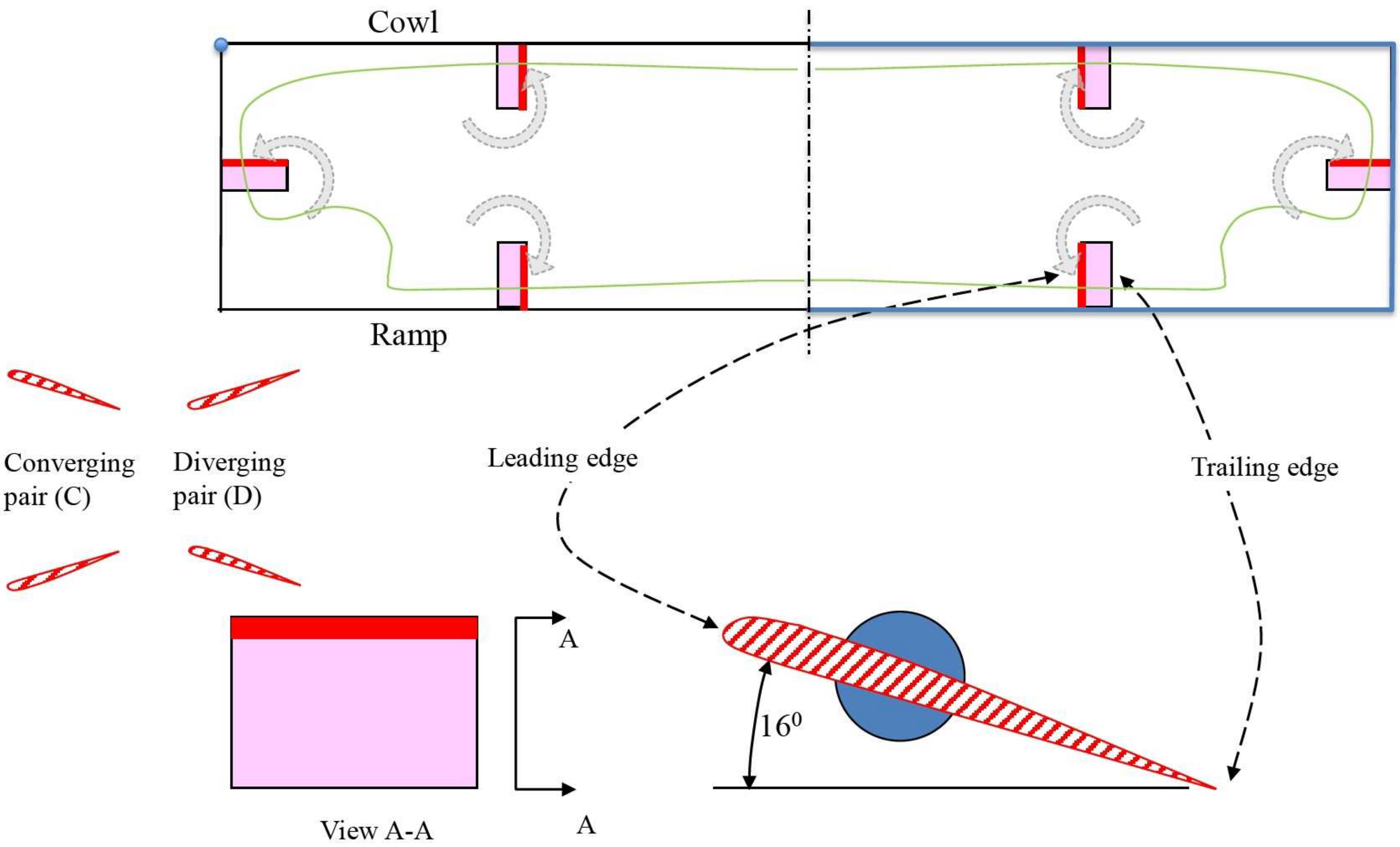


AIP flow field for the Alternate VG Configuration



AIP flow field for Alternate-Opposite VG Configuration

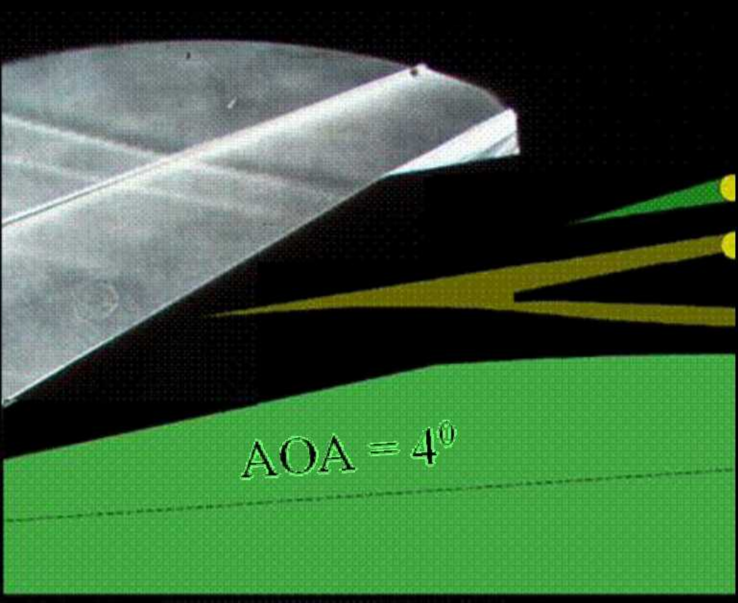
Baseline Configuration



Orientation of vortex generators at station 173.987 (down stream view) Dimensions are presented in the CRD - Figure 27.

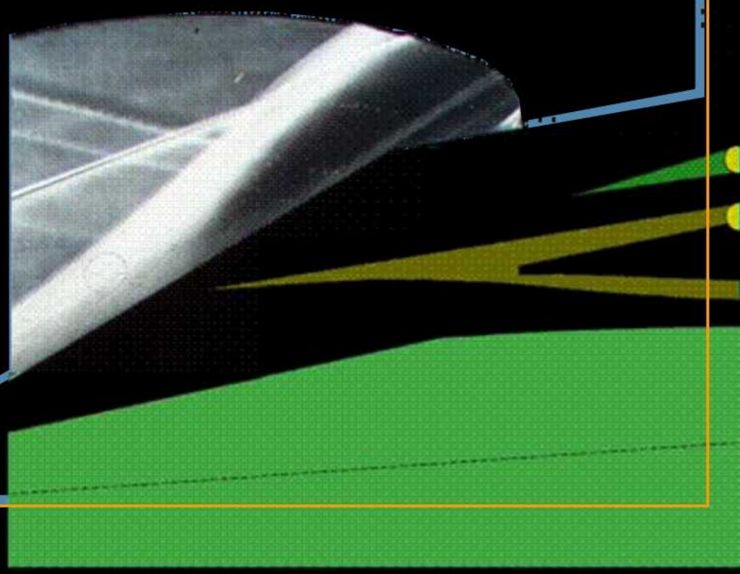
Schlieren video showing buzz: IMX at Mach 4

Started



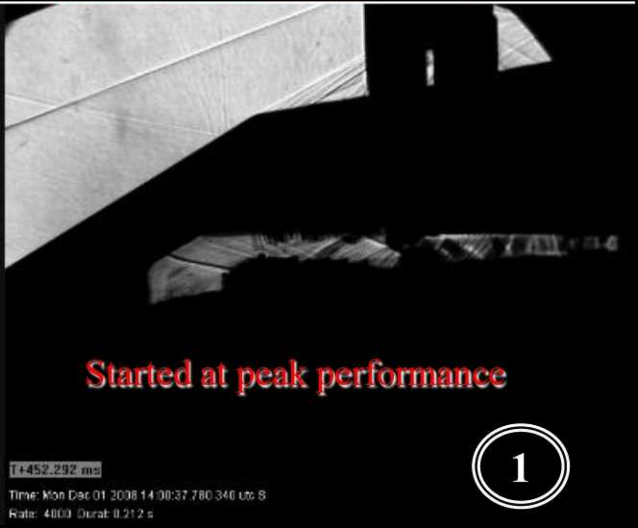
click here

Unstart Video



Inlet Unstart dynamics are severe with high internal comp.

High Speed Schlieren from 1x1 SWT, IMX model



High-Speed Video at Mach 4

Unstart Transient -- 4000 frames/sec